



T.C

YEDITEPE UNIVERSITY

INSTITUTE OF HEALTH SCIENCES

DEPARTMENT OF ENDODONTIC

**IN VITRO EVALUATION OF CYCLIC FATIGUE
RESISTANCE, BENDING RESISTANCE, AND THE
MICROHARDNESS OF DIFFERENT NiTi ALLOY
ROTARY INSTRUMENTS**

DOKTOR OF PHILOSOPHY THESIS

Prepared By:

MOHAMED HSHAD

B.D.S

Istanbul-2021



T.C

YEDITEPE UNIVERSITY

INSTITUTE OF HEALTH SCIENCES

DEPARTMENT OF ENDODONTIC

**IN VITRO EVALUATION OF CYCLIC FATIGUE
RESISTANCE, BENDING RESISTANCE, AND THE
MICROHARDNESS OF DIFFERENT NiTi ALLOY
ROTARY INSTRUMENTS**

DOKTOR OF PHILOSOPHY THESIS

Prepared By:

MOHAMED HSHAD

B.D.S

SUPERVISOR

Assoc. Prof. Dr. Elif Delve Bařer Can

CO-SUPERVISOR

Prof. Dr. Meri Karapınar Kazandağ

Istanbul-2021

APPROVAL

Institute : Yeditepe University Institute of Health Sciences

Programme : PhD

Title of the Thesis : IN VITRO EVALUATION OF CYCLIC FATIGUE RESISTANCE, BENDING RESISTANCE, AND THE MICROHARDNESS OF DIFFERENT NiTi ALLOY ROTARY INSTRUMENTS

Owner of the Thesis : MOHAMED HSHAD

Examination Date : 08/ 09/ 2021

This study have approved as a Doctorate Thesis in regard to content and quality by the Jury.

	Title, Name-Surname (Institution)
Chair of the Jury:	Prof. Dr. Meriç Karapınar Kazandağ (Yeditepe University, Faculty of Dentistry, Endodontic Department)
Supervisor:	Assoc. Prof. Dr. Elif Delve Başer Can (Yeditepe University, Faculty of Dentistry, Endodontic Department)
Member/Examiner:	Prof. Dr. Nimet Gençoğlu (Marmara University, Faculty of Dentistry, Endodontic Department)
Member/Examiner:	Prof. Dr. Feridun Şaklar (Ankara University, Faculty of Dentistry, Endodontic Department)
Member/Examiner:	Assoc. Prof. Dr. Nilüfer Ersan (Yeditepe University, Faculty of Dentistry, Dentomaxillofacial Radiology Department)

APPROVAL

This thesis has been deemed by the jury in accordance with the relevant articles of Yeditepe University Graduate Education and Examinations Regulation and has been approved by Administrative Board of Institute with decision dated and numbered

Prof. Dr. Bayram YILMAZ

Director of Institute of Health Sciences

DECLARATION

I hereby declare that this thesis is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person nor material which has been accepted for the award of any other degree except where due acknowledgment has been made in the text.

Date 08/ 09/ 2021

MOHAMED HSHAD

DEDICATION

I dedicate this thesis to...

My parents

For instilling the value of hard effort and obtaining a higher education.

My wife

For her patience, understanding, and for being a great source of motivation and encouragement.

My daughter

My wonderful love Maysara. Each valuable minute that I spent organizing and writing my thesis was a minute that I wanted to spend with you,

My kinds

May you also be motivated and encouraged to reach your dreams.

ACKNOWLEDGEMENTS

First and foremost, I thank God for receiving and strengthening my prayers, for guiding me throughout my life, and for making the impossible possible.

I express my gratitude to my home nation of Libya for giving me the opportunity and assistance I needed to complete my postgraduate studies.

From the beginning phases of this thesis until the final draft, I owe my deepest gratitude and appreciation to my supervisor, Assoc. Prof. Dr. Elif Delve Bařer Can for her sound advice, providing constructive feedback and careful guidance throughout the whole process.

My sincere thanks also go to my co-supervisor, Prof. Dr. Meri Karapınar Kazandağ, for her innovative ideas and willingness to offer me her time, which helped us to complete this research.

I am thankful to Prof. Dr. Figen Kaptan (Chairman of the Endodontic Department, University of Yeditepe) for her time, effort, and useful suggestions in my academic programs and for reviewing this thesis.

I would like to offer my sincere appreciation to jury members, Prof. Dr. Feridun řaklar and Prof. Dr. Nimet Genođlu for accepting invitations.

I would also like to express my sincerest thanks to Assoc. Prof. Dr. Nilüfer Ersan for her valuable suggestions.

I offer my regards and blessings to Prof. Dr. Jale Tanalp and all members of the Endodontic Department, University of Yeditepe, for their constructive advice and unlimited efforts and assistance.

Lastly but it wasn't a least, I wish to acknowledge and thank my parents for the countless sacrifices they have made throughout the years to provide their children with opportunities they weren't fortunate enough to have. Honest appreciation to my wife, my

daughter and my colleagues. It's your generous delightful love that made my life lighter and happier.



TABLE OF CONTENTS

APPROVAL	ii
DEDICATION	iv
ACKNOWLEDGEMENTS	v
TABLE OF CONTENTS	vii
LIST OF TABLES	xi
LIST OF FIGURES	xv
LIST OF SYMBOLS AND ABBREVIATION	xx
ABSTRACT	xxii
ABSTRACT (Turkish)	xxiv
1. INTRODUCTION AND PURPOSE:	1
2. LITERATURE REVIEW:	5
2.1. Endodontic infection and its treatment	5
2.1.1. Access to the Root Canal System	6
2.1.2. Cleaning and Shaping of The Root Canal System	6
2.1.3. Disinfection of the Root Canal System	7
2.1.4. Sealing of the Root Canal system	7
2.2. Dr. Schilder's Root Canal Shaping Objectives	8
2.3. Root Canal Anatomy	8
2.4. History of Instruments for Root Canal Therapy	11
2.4.1. Endodontic instrumentation and its goals	11
2.4.2. Endodontic Hand Instruments	12
2.4.3. NiTi instruments and Flexibility	13
2.4.4. The rationale for Using NiTi Instruments in Endodontic Treatment	16
2.4.5. Heat Treatment of Rotary NiTi Instruments	17
	vii

2.4.6. NiTi Wire Alloys	20
2.5. Types of Fatigue Failure of Rotary NiTi Instruments	30
2.6. Mechanism of Cyclic Fatigue Failure	33
2.7. Factors Influencing File Separation	34
2.7.1. Operator skill/experience	34
2.7.2. Impact of Instrumentation Technique	35
2.7.3. Impact of Torque Factor	35
2.7.4. Impact of Speed Factor	35
2.7.5. Tooth type, Canal curvature, and Radius Factors	36
2.7.6. Effect of Sterilization and Irrigation	37
2.7.7. Number of Uses	38
2.7.8. Cross-Section Dimensions and Design	38
2.7.9. Impact of Instrument Size and Taper	38
2.7.10. Impact of Manufacturing Process	39
2.7.11. Impact of the Temperature	39
2.8. Prevalence and Incidence of File Separation	39
2.9. Impact of File Separation on the Healing of Endodontic Treatment	41
2.10. Generation of Rotary NiTi Endodontic Files	42
2.10.1. First-Generation Files	42
2.10.2. Second-Generation Files	42
2.10.3. Third-Generation Files	43
2.10.4. Fourth-Generation Files	43
2.10.5. Fifth-Generation Files	44
2.11. Design Features of Protaper Next, Hyflex CM, EdgeFile, and XP-endoShaper	44
2.11.1. The Protaper Next Systems	44
2.11.2. The Hyflex CM Systems	45

2.11.3. The EdgeFile Systems	47
2.11.4. The XP-endoShaper Systems	48
2.12. Up to Date Cyclic Fatigue Studied of a Protaper Next, Hyflex CM, EdgeFile, and XP-end Shaper	50
2.13. Up To Date Bending Resistance Studies of a Protaper Next, Hyflex CM, EdgeFile, and XP-endoShaper	61
2.14. Up To Date Microhardness Studies of a Protaper Next, Hyflex CM, EdgeFile, and XP-endoShaper	63
2.15. Study Models for Cyclic Fatigue Testing	64
2.16. Study Models for Bending Resistance Testing	68
2.17. Study Models for Vicker Microhardness Testing	69
2.18. Aims of the Study	70
2.19. Hypothesis	70
3. MATERIAL AND METHODS:	72
3.1. Methodology Design For the Cyclic fatigue test:	74
3.2. Methodology Design For Bending resistance test:	81
3. 3. Methodology Design For Vickers microhardness test:	83
3. 4. Statistical Analysis:	85
4. RESULTS:	86
4.1. Results of Cyclic Fatigue Test:	86
4.1.1. Effect of File Types, Medium Condition Groups, and Angle of Canal Curvatures on NCF:	86
4.1.2. The Effects of File Types, Medium Condition Groups, and Curvature Locations on NCF:	99
4.1.3. Effect of File Types, Medium Condition Groups, and Angle of Canal Curvatures on the Length of the Separated Part:	105

4.1.4. Effect of File Types, Medium Condition Groups, and Curvature Locations on the Length of the Separated Part:	111
4.1.5. Scanning Electron Microscope Analysis:	117
4. 2. Results of Bending Resistance Test:	126
4. 3. Results of Microhardness Test:	129
5. DISCUSSIONS:	132
6. CONCLUSIONS:	155
7. REFERENCES:	156



LIST OF TABLES

Table 1. Crystallographic structure of individual phases.....	18
Table 2. Definition of the martensitic transformations.	18
Table 3. Overview of NiTi alloy used for the manufacture of endodontic instruments.21	
Table 4. Summary of Characteristics of the studies about Cyclic Fatigue.	50
Table 5. Specifications of the NiTi instruments used in this study.....	72
Table 6. Features of the main automated instrumentation systems used in this study... 73	
Table 7. Study protocol design.....	75
Table 8. Patterns and signs of cyclic fatigue fracture.	79
Table 9. Descriptive statistics (Mean $\pm$ SD, Min/Max, 95% CI) of the NCF values based on medium condition groups, file types, and angle of canal curvatures.....	86
Table 10. Shapiro-Wilk test to determine the normality of distribution of the data (The NCF values based on medium condition groups, file types, angle of canal curvatures).88	
Table 11. Three-way ANOVA test to determine the effects of medium condition groups, file types, and angle of canal curvatures on NCF values.....	88
Table 12. Simple two-way interaction between medium condition groups and file types on NCF values.	89
Table 13. Simple two-way interaction between file types and angle of canal curvatures on NCF values.	89
Table 14. Simple two-way interaction between medium condition groups and angle of canal curvatures on NCF values.	90
Table 15. Simple simple main effect of file types (Mean $\pm$ SD) of NCF values based on medium condition groups and angle of canal curvatures.	90
Table 16. Pairwise comparisons of NCF values between file types-based on medium condition groups and angle of canal curvatures.....	93
Table 17. Simple simple main effect of medium condition groups (Mean $\pm$ SD) of NCF values based on the file types and angle of canal curvatures.....	94
Table 18. Pairwise comparisons of NCF values between medium condition groups based on the file types and angle of canal curvatures.	95
Table 19. Simple simple main effect of angle of canal curvatures on NCF values based on the file types and medium condition groups.....	98

Table 20. Descriptive statistics (Mean $\pm$ SD, Min/Max, 95% CI) of the NCF values based on medium condition groups, file types, and curvature locations.	99
Table 21. Shapiro-Wilk test to determine the normality of distribution of the data (The NCF values based on medium condition groups, ,file types and curvature locations). 101	
Table 22. Three-way ANOVA test to determine the effects of medium condition groups, file types, and curvature locations on NCF values.	101
Table 23. Simple two-way interaction between file types and curvature locations on NCF values.	102
Table 24. Simple simple main effect of curvature locations on NCF values based on file types and medium condition groups.	104
Table 25. Descriptive statistics (Mean $\pm$ SD, Min/Max, 95% CI) of The length of the separated part values based on medium condition groups, file types, and angle of canal curvatures.....	105
Table 26. Shapiro-Wilk test to determine the normality of distribution of the data (The length of the separated part values based on Medium condition groups, file types, and Angle of canal curvatures).....	107
Table 27. Three-way ANOVA test to determine the effects of medium condition groups, file types, and angle of canal curvatures on the length of the separated part values. ...	108
Table 28. The length of the separated part values based on medium condition groups (In both angle of the canal curvatures).	108
Table 29. One-way ANOVA results for the main effect of medium condition groups on the length of the separated part values (In both angle of the canal curvatures).....	109
Table 30. The length of the separated part values based on the file types (In both angle of the canal curvatures).	109
Table 31. One-way ANOVA results for the main effect of file types on the length of separated part values (In both angle of canal curvatures).....	109
Table 32. The length of the separated part values based on the angle of canal curvatures.	110
Table 33. Independent samples t-test for the main effect of angle of the canal curvatures on the length of the separated part values.....	110

Table 34. Descriptive statistics (Mean $\pm$ SD, Min/Max, 95% CI) of The length of the separated part values based on medium condition groups, file types, and place of curvature locations.....	111
Table 35. Shapiro-Wilk test to determine the normality of distribution of the data (The length of the separated part values based on medium condition groups, file types , and curvature locations).....	113
Table 36. Three-way ANOVA test to determine the effects of medium condition groups, file types, and curvature locations on the length of the separated part values.....	114
Table 37. The length of the separated part values based on medium condition groups (In both of curvature locations).	114
Table 38. One-way ANOVA results for the main effect of the medium condition groups on the separated part values (In both of curvature locations).....	114
Table 39. The length of the separated part values based on the file types (In both of curvature locations).....	115
Table 40. One-way ANOVA results for the main effect of file types on the separated length values (In both of curvature locations).	115
Table 41. The length of the separated part values based on curvature locations.	116
Table 42. Independent samples t-test for the main effect of curvature locations.	116
Table 43. Descriptive statistics (Mean $\pm$ SD, Min/Max, 95% CI) for bending resistance based on the file types.....	126
Table 44. Shapiro-Wilk test to determine the normality of distribution of the data (Bending resistance values based on file types).	127
Table 45. One-way Welch's ANOVA results for the effect of file types on bending resistance.....	128
Table 46. Games-Howell post hoc analysis for pairwise comparisons of bending resistance between file types.....	128
Table 47. Descriptive statistics (Mean $\pm$ SD, Min/Max, 95% CI) for Vickers microhardness based on the file types.	129
Table 48. Shapiro-Wilk test to determine the normality of distribution of the data (VHN values based on file types).....	130
Table 49. One-way Welch's ANOVA results for the effect of file types on microhardness.	131

Table 50. Games-Howell post hoc analysis for pairwise comparisons of Vickers microhardness between file types.	131
--	-----



LIST OF FIGURES

Figure 1. Elbow formation and apical zipping in a curved maxillary canine #23(left), and Ledge at the outer side of the root canal curvature in #22 (middle left). Strip perforation at the inner side of the curvature in MB root of #46 (middle right). Apical perforation of tooth #44 (right).	7
Figure 2. Diagram of double curvature canal in proximal view of the mesial root of the lower molar. The angle is measured at the intersection of lines b and c and c and d. Vector 2 is the direction of transport during instrumentation. Note shorter ML root (average, 0.75 mm).	9
Figure 3. A schematic description of the digitally measured straight distances (tangents), angles, and curvature localization of one selected maxillary lateral incisor (left), maxillary premolar (Right).	10
Figure 4. Canal curvature calculation as per Schneider (A1 and A2) and Pruett <i>et al.</i> (B1 and B2).	10
Figure 5. Stress-strain curve: stainless steel (red line) and nickel-titanium (black line). Elastic limit = maximum stress without permanent deformation; fracture limit = stress at which fracture occurs; elongation % refers to the deformation that results from the application of tensile stress, calculated as (change in length/ original length) x 100%. 16	
Figure 6. Schematics of crystal structures and microstructures of martensite, R- phase, and austenite.	17
Figure 7. Martensitic transformations. (a) Superelasticity (SE) at ambient temperature above the austenite finish temperature (Af). (b) Shape memory effect (SME). For the martensite reorientation (MR), less stress is required than for stress-induced martensite (SIM) transformation. (Ms = martensite start temperature).	19
Figure 8. Temperature hysteresis diagram of NiTi alloy. (Ms) martensite start temperature, (Mf) martensite finish temperature, (As) austenite start temperature, (Af) austenite finish temperature.	20
Figure 9. Schematic stress-strain diagram of conventional NiTi (black) and M-Wire (red) displaying the yielding phenomenon (YP) resulting in a lower initial elastic modulus of M-Wire ($\Delta E1$) compared with conventional NiTi ($\Delta E2$). The stress plateau occurs due to stress-induced martensite (SIM) transformation.....	23

Figure 10. Stress-strain-temperature diagram showing the shape memory effect of martensitic NiTi instruments (e.g. Hyflex CM). The stress-plateau occurs due to martensite reorientation (MR).	24
Figure 11. (a) Spring-back effect of austenitic NiTi alloys (b) controlled memory effect of martensitic NiTi alloys.	26
Figure 12. Electrical discharge machining (left). (1) Ionization of the dielectric liquid (2) Spark (3) Vaporization of a small particle (4) Resolidification. Basic components of EDM (Right).	28
Figure 13. Schematic drawing of various regions for cyclic fatigue failure.	33
Figure 14. Illustrated Characteristic and Design Features of Protaper Next.	45
Figure 15. Illustrated Characteristic and Design Features of Hyflex CM files.	47
Figure 16. Illustrated Characteristic and Design Features of EdgeFiles.	48
Figure 17. Illustrated Characteristic and Design Features of XP-endoShaper.	49
Figure 18. Devices for cyclic fatigue testing: (a) Glass or metal tube, (b) Inclined plane, (c) Grooved block and rod, (d) Two-pin jig, (e) Three-pin jig, and (f) Custom-machined canals.	67
Figure 19. Illustrated Customized Devices for Bending Resistance Testing. (a) Schematic drawing for bending stiffness, (b) Flexibility testing apparatus with 4.5mm deflection, (c) cantilever bending testing, (d) jig used for flexibility testing, (e) The 45 ⁰ bending test apparatus, and (f) boundary conditions for the bending testing.	69
Figure 20. NiTi instruments were used in this study. (a) PTN, (b) Hyflex CM, (C) EdgeFile and (d) XP-endoShaper.	73
Figure 21. (a) Cyclic fatigue testing jig with simulated canals at 90 ⁰ and S-shape, and fatigue test of an experimental file in the block, (b) Experimental setup showing the clamping mechanism of the handpiece for the TF adaptive endo motor system with an experimental file inserted in the simulated canal at the room temperature, (c). Experimental setup showing the TF adaptive motor, cyclic fatigue test device, and aquarium thermostat and aquarium digital thermometer in a glass aquarium filled with sodium hypochlorite at 37.0 ⁰ C and (d) Measurement of a separated fragment of the file with digital caliber.	80
Figure 22. (a). A schematic drawing diagram of a bending resistance test device, (b). Experimental setup showing experimental file fastened in the self-cure acrylic at 3mm	

from the tip and on the other side of the file showing loading force onto the shaft of instruments using Instron universal testing machine, and (c) Experimental file bent 45° at the tip.	82
Figure 23. Experimental setup showing, (a) low-speed diamond saw, (b) grinder/polisher machine, (c) Experimental grinding fragment file embedded in the self-cure acrylic, (d) digital microhardness tester, (e) A diamond indenter onto an experimental file, (f) A schematic drawing diagram of a microhardness test device, and (g) Example of a well-formed Vickers indentation from the google.	84
Figure 24. The line graph showed descriptive NCF values based on medium condition groups, file types, and angle of canal curvatures.	87
Figure 25. The line graph showed descriptive statistics of NCF values based on medium condition groups, file types, and curvature locations	100
Figure 26. The line graph showed descriptive statistics of the length of the separated part values based on medium condition groups, file types, and angle of canal curvatures.	106
Figure 27. The line graph showed descriptive statistics the length of the separated part values based on medium condition groups, file types, and curvature loactions.	112
Figure 28. Longitudinal SEM images for view fractured Protaper Next rotary files at a magnification of 250X and showing back scattered micrograph of fracture site with irregular cracks near to fracture site (<i>blue arrow</i>), disruption of the cutting edges, grooves and surface pitting (<i>red arrows</i>), and debris (<i>yellow arrows</i>).	118
Figure 29. Representative scanning electron microscopy images showing cross-sections of fractured Protaper Next instruments after cyclic fatigue. Left column (A, C, E, and G) at lower magnification; 500X view of fracture surfaces of the test instruments showed the crack initiation origin (<i>red arrows</i>). Right column (B, D, F, and H)) at higher magnification; 5000X view of dimpled areas covered almost all the cross-section areas with the characteristic surface pattern of fatigue failure. Presence of fatigue striations (<i>yellow arrows</i>), microvoids (<i>white arrows</i>), inclusions (<i>black arrow</i>). Ductile fracture roughness was evidence in all the samples (A to H).	119
Figure 30. Longitudinal SEM images for view fractured Hyflex CM rotary files at a magnification of 250X and showing back scattered micrograph of fracture site with irregular cracks near to fracture site (<i>blue arrows</i>), disruption of the cutting edges, grooves and surface pitting (<i>red arrows</i>), and debris (<i>yellow arrows</i>).	120

Figure 31. Representative scanning electron microscopy images showing cross-sections of fractured Hyflex CM instruments after cyclic fatigue. Left column (A, C, E, and G) at lower magnification; 500X view of fracture surfaces of the test instruments showed the crack initiation origin (*red arrows*). Right column (B, D, F, and H)) at higher magnification; 5000X view of dimpled areas covered all cross-section areas with the characteristic surface pattern of fatigue failure. Presence of fatigue striations (*yellow arrows*), microvoids (*white arrows*), crater-like formation (*orange arrow*). Ductile fracture roughness was evidence in all the samples (A to H). 121

Figure 32. Longitudinal SEM images for view fractured EdgeFile rotary files at a magnification of 250X and showing back scattered micrograph of fracture site with irregular cracks near to fracture site (*blue arrows*), disruption of the cutting edges, grooves and surface pitting (*red arrows*), debris (*yellow arrows*). 122

Figure 33. Representative scanning electron microscopy images showing cross-sections of fractured EdgeFile instruments after cyclic fatigue. Left column (A, C, E, and G) at lower magnification; 500X view of fracture surfaces of the test instruments showed the crack initiation origin (*red arrows*). Right column (B, D, F, and H)) at higher magnification; 5000X view of centralized dimpled areas with the characteristic surface pattern of fatigue failure. Presence of fatigue striations (*yellow arrows*), microvoids (*white arrows*), inclusions (*black arrow*), and multiple surface micro-cracking (*green arrows*). Ductile fracture roughness was evidence in all the samples (A to H). 123

Figure 34. Longitudinal SEM images for view fractured XP-endoShaper rotary files at a magnification of 250X and showing back scattered micrograph of fracture site with irregular cracks near to fracture site (*blue arrow*), disruption of the cutting edges, grooves and surface pitting (*red arrow*), corrosion (*green arrows*), and debris (*yellow arrows*). 124

Figure 35. Representative scanning electron microscopy images showing cross-sections of fractured XP endoShaper instruments after cyclic fatigue. Left column (A, C, E, and G) at lower magnification; 500X view of fracture surfaces of the test instruments showed the crack initiation origin (*red arrows*). Right column (B, D, F, and H)) at higher magnification; 5000X view of dimpled areas covered all the cross-section areas with the characteristic surface pattern of fatigue failure. Presence of fatigue striations (*yellow*

<i>arrows</i>), microvoids (<i>white arrows</i>), inclusions (<i>black arrow</i>). Ductile fracture roughness was evidence in all the samples (A to H).....	125
Figure 36. Bar chart comparison of bending resistance based on the file types.....	126
Figure 37. Bar chart comparisons of Vickers microhardness based on the file types.	129



LIST OF SYMBOLS AND ABBREVIATION

Af	Austenite Finish
AR	Asymmetric Rotary
As	Austenite Start
ASTM	American Society for Testing and Materials
CFR	Cyclic Fatigue Resistance
CM	Control Memory
DSC	Differential Scanning Calorimetry
EDM	Electrical Discharge Machining
EF	EdgeFile
FEA	Finite Element Analysis
FL	Fragment Length
GF	Gram Force
HCM	Hyflex CM
IS	Instrument Separation
MF	Martensite Finish
MR	Martensite Reorientation
NCF	Number of Cycles to Failure
OC	OneCurve
OS	OneShape
PDL	ProDesign Logic
PTG	Protaper Gold
PTN	Protaper Next

PTU	Protaper Universal
RC	Race
SA	Stable Austenite
SCC	Stress Corrosion Cracking
SE	Superelasticity
SEM	Scanning Electron Microscope
SIM	Stress-Induced Martensite
SME	Shape Memory Effect
TF	Twisted File
TRN	TruNatomy
TRS	TRUShape
TS	2Shape
UTS	Ultimate Tensile Strength
VB	Vortex Blue
VHN	Vickers Microhardness
WOG	WaveOne Gold
XPS	XP EndoShaper
XRD	X-Ray Diffraction

ABSTRACT

Hshad, M (2021). **In Vitro Evaluation of Cyclic Fatigue Resistance, Bending Resistance, and the Microhardness of Different NiTi Alloy Rotary Instruments.** Yeditepe University Institute of Health Sciences. Faculty of Dentistry, Department of Endodontic, PhD Thesis, Istanbul. This study was conducted to compare the mechanical properties of the Protaper Next (PTN), Hyflex CM, EdgeFile, and XP -endoShaper, and to analyze the influence of the temperatures, sodium hypochlorite (NaOCl) immersion, and sterilization on the cyclic fatigue resistance of these instruments in a single and double (S- shape) canal curvatures. Four types of Nickel-Titanium (NiTi) rotary instruments: Protaper Next- X3 (30/0.07), Hyflex CM (30/0.04), EdgeFile- X7 (30/0.04), and XP-endoShaper (30/0.01) were evaluated. Each brand of the NiTi instruments was divided into 4 groups (n=20/each group; 10/subgroup) during the cyclic fatigue test as followed: Group 1 (control group) was composed of new instruments without immersed in NaOCl or subjected to autoclave sterilization at room temperature. Group 2 was composed of instruments with immersed in 5% NaOCl solution without sterilization at body temperature, Groups 3 was composed of instruments with immersed in 5% NaOCl solution and 1-time sterilization at body temperature. Groups 4 was composed of instruments immersed in 5% NaOCl solution with 5-times sterilization at body temperature. The number of cycles to failure (NCF) was calculated. The fracture surface of instruments was assessed by using a scanning electron microscope (SEM). The files were tested for bending resistance by using a cantilever- bending test (n=20/each brand). Vickers microhardness was measured on the cross-section of instruments with 300-g load and 15-second dwell time (n=20/each brand). Statistical analysis was carried out using a three-way analysis of variance (ANOVA) and Bonferroni's post hoc analysis for cyclic fatigue test, and one-way analysis of variance (ANOVA) and Games-Howell post hoc analysis for bending resistance and microhardness tests. The statistical significance level was established at $p < 0.05$. The results show that, the difference in the NCF of all the instruments was statistically significant ($p < 0.05$). The NCF of EdgeFile and XP -endoShaper were higher than Hyflex CM and PTN ($p < 0.05$) in all tested groups. The NCF was significantly influenced by the file types ($p < 0.05$) in all tested groups, angle and curvature locations ($p < 0.05$) in all tested files except PTN ($p > 0.05$), and

surrounding medium conditions ($p < 0.05$) in all tested files except PTN and Hyflex CM ($p > 0.05$). No statistical difference in the length of the separated part at all tested groups ($p > 0.05$) except at angle and curvature locations ($p < 0.05$). The ranking in bending resistance values was as follows: PTN > HCM > EdgeFile > XP-endoShaper. The order of the microhardness test from lowest to highest values was as follows: Hyflex CM < XP-endoShaper < PTN and EdgeFile, and there was no statistical difference between PTN and EdgeFile ($p > 0.05$). In conclusion, EdgeFile significantly outperforms other brands in terms of fatigue resistance, followed by XP-endoShaper. All files except PTN showed a significant decrease in NCF in more challenging canals. The NCF of both EdgeFiles and XP-endoShaper is harmed by body temperature and NaOCl immersion, whereas sterilization has a favorable influence on EdgeFile's NCF but a detrimental one on XP-endoShaper's. In comparison to the other brands examined, XP-endoShaper demonstrated the most flexibility, followed by EdgeFile. When compared to other brands, PTN and EdgeFiles showed greater wear resistance.

Keywords: Mechanical properties, NiTi rotary instruments, body temperature, irrigation, sterilization.

ABSTRACT (Turkish)

Hshad, M (2021). **Farklı NiTi Alaşımlarından Yapılmış Döner Aletlerin Döngüsel Yorgunluk Direncinin, Bükülme Direncinin, ve Mikrosertliğinin in Vitro Değerlendirilmesi.** Yeditepe Üniversitesi Sağlık Bilimleri Enstitüsü. Diş Hek, Endodonti, Doktora Tezi. Bu çalışma Protaper Next (PTN), Hyflex CM, EdgeFile, and XP-endoShaper kanal eğelerinin mekanik özelliklerinin incelenmesi ve ısı, sodium hipoklorit (NaOCl) ve sterilizasyonun bu eğelerin döngüsel yorgunluk direnci üzerinde etkilerinin tek kurvatürlü ve S şekilli kanallarda analiz edilmesi. Dört farklı tip Nikel-Titanyum (NiTi) döner alet: Protaper Next X3 (30/0.07), Hyflex CM (30/0.04), EdgeFile X7 (30/0.04) ve XP-endoShaper (30/0.01) değerlendirildi. Her tip döner alet, döngüsel yorgunluk testi sırasında aşağıdaki gibi 4 gruba (n=20/her grup; 10/alt grup) ayrıldı: Grup 1 (kontrol grubu); oda sıcaklığında, NaOCl solüsyonuna daldırılmayan ve otoklav sterilizasyonuna girmeyen yeni aletlerden oluşturuldu. Grup 2; vücut sıcaklığında %5'lik NaOCl solüsyonuna daldırılan ve sterilizasyona girmeyen, Grup 3; vücut sıcaklığında %5'lik NaOCl solüsyonuna daldırılan ve bir defa sterilizasyona giren aletlerden oluşturuldu. Grup 4; vücut sıcaklığında %5'lik NaOCl solüsyonuna daldırılan ve 5 defa sterilizasyona giren aletleri içerdi. Aletlerin kırılıncaya kadar gerçekleştirdiği tur sayısı (KKTS) hesaplandı. Aletlerin kırık yüzeyleri tarama elektron mikroskobu ile (SEM) incelendi. Aletler cantilever-bükülme testi kullanılarak bükülme direnci açısından test edildi. Vickers mikrosertliği, aletlerin enine kesitinde 300-g yük ve 15 saniye bekleme süresi ile ölçüldü (n=20/ her marka). İstatistiksel analiz, döngüsel yorulma testi için üç yönlü varyans analizi (ANOVA) ve Bonferroni'nin post hoc analizi ve eğilme direnci ve mikrosertlik testleri için tek yönlü varyans analizi (ANOVA) ve Games-Howell post hoc analizi kullanılarak yapıldı. İstatistiksel anlamlılık düzeyi $p < 0.05$ olarak belirlendi. Sonuç şunu gösteriyor, tüm aletlerin KKTS farkları istatistiksel olarak anlamlıdır ($p < 0.05$). EdgeFile ve XP-endoShaper'ın KKTS, test edilen tüm gruplarda Hyflex CM ve PTN'den ($p < 0.05$) daha fazladır. KKTS, döner alet tipinden ($p < 0.05$) test edilen tüm aletlerde, kurvatür açısı ve lokasyonundan ($p < 0.05$) PTN hariç ($p > 0.05$) test edilen tüm aletlerde, çevre koşullarından ($p < 0.05$) PTN and Hyflex CM hariç ($p > 0.05$) test edilen tüm aletlerde anlamlı olarak etkilenmiştir. Açı ve kurvatür lokasyonu dışında ($p < 0.05$) tüm test gruplarında ($p > 0.05$) kırık parçanın uzunluğunda istatistiksel bir fark yoktur (p

< 0.05). Bükülme direnci değerlerinde sıralama; PTN > HCM > EdgeFile > XP-endoShaper şeklindedir. Mikrosertlik testinin en düşük değerden en yükseğe doğru sıralaması: Hyflex CM<XP-endoShaper<PTN ve EdgeFile şeklindedir PTN ve EdgeFile arasında istatistiksel bir fark yoktur ($p > 0.05$). Sonuç olarak EdgeFile, yorulma direnci açısından diğer aletleri önemli ölçüde geride bırakmıştır, EdgeFile'ı XP-endoShaper takip etmektedir. PTN dışındaki tüm eğeler, daha zorlu kanallarda KKTS bakımından önemli bir düşüş göstermiştir. EdgeFile ve XP-endoShaper'ın KKTS vücut sıcaklığı ve NaOCl solüsyonu içerisine daldırmasından negatif yönde etkilenirken, sterilizasyon EdgeFile'ın KKTS'nı olumlu etkilemiş fakat XP-endoShaper üzerinde yıkıcı etkileri olmuştur. Diğer aletlerle karşılaştırıldığında en fazla esnekliği XP-endoShaper gösterirken onu EdgeFile izlemiştir. PTN ve EdgeFile diğer aletlere göre daha fazla aşınma direnci göstermiştir.

Anahtar Kelimeler: Mekanik özellikler, NiTi döner aletler, vücut sıcaklığı, irigasyon, sterilizasyon.

1. INTRODUCTION AND PURPOSE:

Nickel Titanium (NiTi) alloy has unique properties that have allowed it to be added to a select group of "exotic" or "smart" materials. These materials have one or more properties that can be dramatically altered by external stimuli in a controlled manner. Such materials may even be supposed to have the potential for 'smart' behavior, i.e. They can respond to changes in the environment to result in beneficial changes in the material's properties, either inside the material itself or in the material-tooth complex(1). NiTi, for example, can suffer large deformations (strains) that can be induced or recovered through temperature or stress (shape) change. Some of these material's properties, particularly their superelastic properties, have led to them being favored as the material of choice for rotary NiTi endodontic instruments(2). The application of NiTi in endodontics was reported first by Walia *et al*, 1988(3).

NiTi's unique material properties make it ideal for use in endodontic rotary instruments. Because the property and performance of endodontic files can significantly affect the outcome of root canal shaping and cleaning, this development has triggered a significant amount of research aimed for improving metallic properties to improve clinical performance and safety. With improvements in file design and cost-effective manufacturing, this study has resulted in rotary NiTi instruments with higher reliability, durability, and performance. Instrument flexibility, fatigue resistance, and cutting efficiency have been improved as a consequence of incorporating surface engineering (implantation or electropolishing) and/or microstructure control (heat treatment or new manufacturing procedures) into endodontic file design(2).

The rationale for using rotary NiTi instruments in endodontics requires a brief discussion of their metallurgical properties and manufacturing processes. This was covered in the study of literature section, which aimed to better understanding of current advancements in rotary NiTi technology.

Despite the benefits of rotational NiTi instruments, many authors and clinicians have expressed worry regarding the potential of a rotating NiTi instrument separating

within the root canal system during endodontic treatment. The fracture of an endodontic instrument within the root canal is a complex happening. The fracture may occur with or without warning and any visible defects of previous permanent deformation. Also, the presence of a fractured instrument within the space of a root treated tooth is an unwanted occurrence for the practicing dentist and the patient. The effort of removing broken files is complicated by the possibility of requiring surgical intervention and the annoyance of the patient. Two modes of fracture of rotary NiTi endodontic instruments have been recognized in the clinical situation: Cyclic fatigue and torsional failure. Amongst these, cyclic fatigue is a significant factor from a clinical point of view(4).

A review of the literature also revealed that specific properties of rotary NiTi files, as well as other important factors such as root canal anatomy in terms of radius and degree of curvature, operator skill, operational speed and torque, previous use, sterilization procedures, cross-sectional part and design of the instrument, play a role in file failure. As a result, numerous attempts to increase the fracture resistance of NiTi instruments have been made, including heat treatments, alternative cross-sectional designs, surface treatment, and alloy metallurgical enhancements.

ProTaper Next files (PTN; Dentsply Maillefer 2013) have been introduced to the market. According to the manufacturer, these files include an off-centered rectangular cross-section design for improved strength and a unique asymmetric rotating motion that further enhances canal shaping efficiency. They are manufactured using M-Wire NiTi alloy to improve the files' flexibility and cycle fatigue resistance(5). HyFlex CM rotary files (HCM; Coltene Endo/Whaledent, Inc, Cuyahoga Falls, OH, USA) are manufactured from a new type of NiTi wire, namely CM wire (controlled memory), using a special thermomechanical process, making the files extremely flexible but without the shape memory of conventional NiTi files(6). Another file system released very recently and made of a CM alloy, the EdgeFile X7 (EFX7; EdgeEndo, USA), has a modified convex triangular cross-section. Based on internal cyclic fatigue testing by manufacture, this instrument is made of an Annealed Heat Treated (AHT) NiTi alloy brand termed Flexible Fire-Wire, which enhances the strength of the loading files by two to eight times. In addition, "Canal Contouring Technology" improves the material's characteristics, making

the files highly flexible while reducing the shape memory and straightening effect that conventional NiTi files have(7). Recently, XP-endoShaper (XPS; FKG Dentaire, La Chaux-de-Fonds, Switzerland) instruments have been introduced. XPS is available in one size 30, 0.01 taper which is produced from NiTi MaxWire (Martensite-Austenite Electropolishing-Flex, FKG) alloy. At body temperature, the MaxWire alloy allows the instruments to adapt to temperature fluctuations and take a preset shape inside the root canal(8).

Instrument fractures occur in a dynamic process in clinical practice and can be caused by flexural and torsional stresses. However, these factors should be taken into attention to prevent unpredicted instrument fractures.

With an understanding of cyclic fatigue and torsion failure of rotary NiTi instruments, conclusions were drawn from the information given in the literature review sections to develop and test a research question in the form of a null hypothesis. Also, because there have been few investigations on XP-endoShaper and EdgeFile's resistance to cyclic stress and other mechanical properties, so we conducted a comprehensive study to increase the evidence.

The study aims to test the cyclic fatigue, bending resistance, and microhardness of Protaper Next (PTN; Dentsply Maillefer, Ballaigues, Switzerland), HyflexCM™ (HCM; Colten Endo/Whaledent, Inc, Cuyahoga Falls, OH, USA), EdgeFile –X7 (EFX7, EdgeEndo, USA), and XP-endoShaper files (XPS; FKG Dentaire, La Chaux-de-Fonds, Switzerland). To get information on the impact of different canal curvatures and other influencing factors on cyclic fatigue failure, and to investigate the effect of different NiTi alloys on the bending resistance and microharshness, an appropriate research methodology was considered.

The data was analyzed with a statistical software package, then graphed and discussed. Based on the significance level used in the statistical analysis, the null hypothesis was rejected.

The study's limits and shortcomings were acknowledged, and recommendations were given that might help to improve the scientific base of cyclic fatigue and other mechanical properties in rotating NiTi files.

To conclude up this research, a detailed discussion was written. The findings were applied to clinical endodontic therapy, and recommendations for the use of rotating NiTi instruments in particular situations were made.



2. LITERATURE REVIEW:

2.1. Endodontic infection and its treatment

The definitive biological objective of the endodontic treatments is either to prevent or cure apical periodontitis(9). The presence or absence of microbial flora was the main factor in the healing of exposed rodent pulps(10). Endodontic infection occurs especially in root canals that lack host defenses, either due to pulp necrosis (caused by caries, trauma, periodontal disease, or iatrogenic operative procedures) or pulp removal (treatment). Bacteria are the most common microorganisms linked to the development of apical periodontitis. Bacteria inhabiting the root canal system use apical and lateral foramina, as well as root perforations, to obtain access to the peri-radicular tissues. Inflammatory and immunologic responses occur in the peri-radicular tissues as a result of the conflict between bacteria and host defenses. These defensive systems, while protective, can also be damaging, causing apical periodontitis to develop. Endodontic infections can cause acute or chronic apical periodontitis, depending on a variety of bacterial and host-related variables. Apical periodontitis can be clinically symptomatic or asymptomatic, as histological abnormalities may not usually correspond with clinical symptoms. Bacteria had invaded the root canal system at this point. Because of the absence of blood circulation in the necrotic pulp, the human immune system, which has been activated and is attempting to remove the hazardous invading germs, is unable to efficiently reach the bacteria in the root canal. As a result, dental treatment was required to eradicate the bacteria and, as a result, the infection. This can be accomplished by tooth extraction or root canal treatments(11).

After a proper diagnosis, root canal treatment consists of the first step of mechanical cleaning and shaping with the help of irrigation solutions, and a final step of canal obturation with the involvement of an adequate coronal restoration. Mechanical instrumentation of the canal system has multiple roles: reduction of bacterial load, removal of debris and organic tissues, and creation of space for the irrigation solutions and the root filling(12). When a tooth is diagnosed with a pulpal or periapical infection, conventional root canal treatment is recommended. The main purpose of endodontic

therapy is to improve the success rate of the treatment provided. It is divided into four categories(13). These were: 1) Access to the root canal system, 2) Cleaning and shaping of the root canal system, 3) Disinfection of the root canal system, and lastly, 4) Sealing of the root canal system and access cavity.

2.1.1. Access to the Root Canal System

Despite the fact that it is the initial stage in the treatment, clinicians must consider how to accomplish the following three goals in addition to removing the pulp canal chamber's contents. The foundation of a suitable access cavity is the ability to locate all canal orifices. Furthermore, having a suitable access cavity is beneficial for shaping and cleaning procedures, as it reduces the risk of file separation while cutting the dentine walls in each canal. Files that are not appropriately exposed to the chamber or that enter at substantial angles to the general long axis of the root canal/root might cause stress on the file, which can lead to fracture. The correct access cavity also functions as a reservoir for irrigation fluid, which aids in shaping and cleaning the root canal system by acting as a lubricant and removing dentinal debris from the canal system(13).

2.1.2. Cleaning and Shaping of The Root Canal System

Clinicians can go on to the second aim, cleaning and shaping the root canal system, if the correct access cavity has been created with straight-line access to all of the canal's orifices. The files' fundamental function is to remove the pulp tissues and other substances from the root canal, and they do this by mechanical action (either by hand or motor-assisted) of the files. The removal of the vital but inflamed pulp, infected dentine, or existing root canal filling material, in the sequence listed above, gives a better dentinal surface on which irrigants or other products can exert their activity. It should be highlighted that the above-mentioned beneficial effects of mechanical enlargement of a root canal can be destroyed if the canal over enlarged by preparation. In the search for greater canal cleanliness by way of mechanical means, the weakened root structure is more predisposed to root fracture. Also, the risk of iatrogenic root canal alterations, such

as ledges or strip perforations, or file separation increase with the use of progressively larger files(13) (Figure 1).

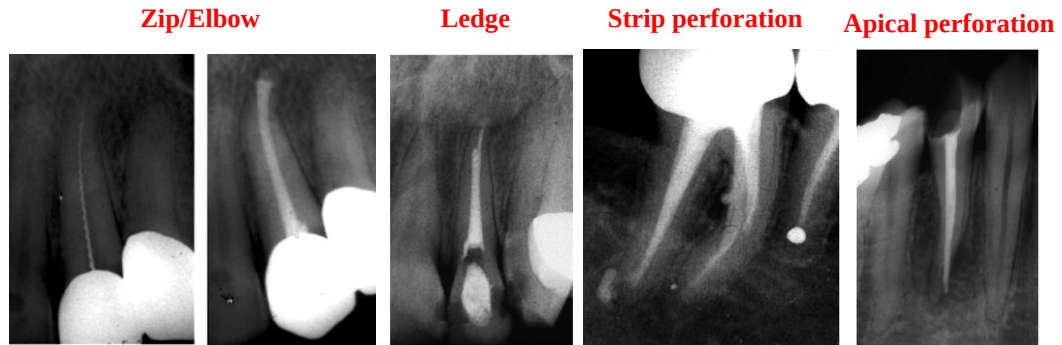


Figure 1. Elbow formation and apical zipping in a curved maxillary canine #23(left), and Ledge at the outer side of the root canal curvature in #22 (middle left). Strip perforation at the inner side of the curvature in MB root of #46 (middle right). Apical perforation of tooth #44 (right).

2.1.3. Disinfection of the Root Canal System

The use of modern irrigant solutions and procedures required thorough root canal preparations in order to achieve optimal disinfection of the root canal system. The narrow size of most root canals, as well as the numerous irregularities within them, would prevent the irrigant's solution from properly acting and diffusing. The last two objectives are mostly served by the previously listed two objectives (i.e.: disinfection and obturation of the root canal system). The keys to successful root canal disinfection are to achieve excellent cleaning and shaping, as well as a dependable and smooth connection from the canal orifice to the apical terminus of the root canals system(13).

2.1.4. Sealing of the Root Canal system

After root canal preparation and disinfection, the essential goal of effective root canal therapy is to prevent pathogenic material from entering the root canal system from either the coronal or apical side of the root canal by perfect root canal sealing. Leakage from a defective filling in the access cavity or subsequent decay reaching the pulp chamber are examples of coronal reintroduction of bacteria following root canal

treatment. Residual pathogens in an apical delta might have re-entered the root canal area and triggered a periapical inflammatory response, resulting in apical reintroduction. Existing root canal fillings and sealers require sufficient space in the root canal to be correctly inserted and subsequently modified according to the clinician's desires. Cleaning and shaping also serve the function of producing a correct track from the opening at the chamber's floor to the apical terminal of the root canal to better seal the root canal system tridimensionally and avoid reinfection, as mentioned previously(13).

2.2. Dr. Schilder's Root Canal Shaping Objectives

Dr. Schilder's conclusive role in endodontics was replicated in the five objectives stated below, and many clinicians doing root canal therapy still need it(14). 1) A continuously tapering funnel from apex to access cavity. 2) A cross-sectional diameter of the root canal should be narrower at every point apically. 3) The root canal preparation should path with the shape of the original root canal. 4) The apical foramen should remain in its original position. 5) An apical foramen kept as small as practical. These guidelines were regularly used as the standard for which a shaped and cleaned root canal is assessed to determine if procedural errors have occurred during the mechanical root canal preparation.

2.3. Root Canal Anatomy

Several studies have identified various shapes and configurations of both the roots and their related canals in this regard. In vivo or ex vivo radiography, cleared teeth, or micro-CT examinations were among the methods used. Root canal angulation from a mesiodistal plane, which is generally the only plane visible during a radiographic evaluation in a clinical environment, provides the most information. The root canal angulation for a buccolingual plane has been documented by almost bits of intelligence(15–18). This plane was parallel to the x-ray beam and does not deal with any information on root canal curvature unless a sufficient horizontal shift during conventional two-dimensional radiography or a three-dimensional image with the aid of

cone-beam computed tomography (CBCT) was taken. The presence of more than one curvature in a root canal can be unpredicted if the clinician is not aware of looking for such buccolingual curvature or they were not noticeable when the radiographic exam is performed. Schäfer *et al* stated a secondary or “S-shape” canal curvature as high as 59.0% of the mesiobuccal root of mandibular second molars(18) (Figure 2). Willershausen *et al* described two curvatures in maxillary incisors in 9.7% of the samples examined and between 11.3%-26.0% for either the buccal or palatal root of either the maxillary first or second premolar(16,17) (Figure 3).

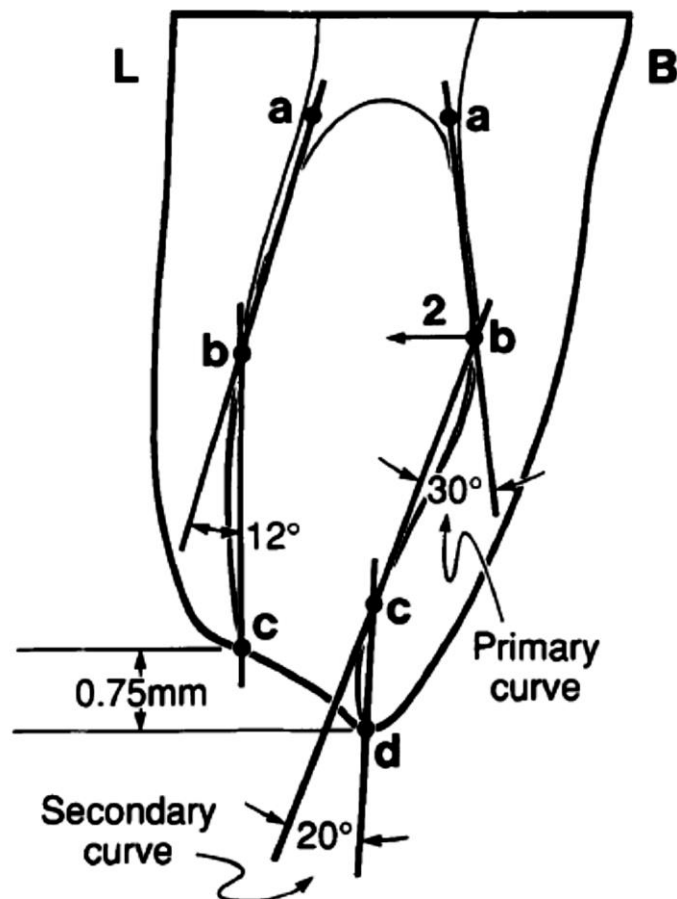


Figure 2. Diagram of double curvature canal in proximal view of the mesial root of the lower molar. The angle is measured at the intersection of lines b and c and c and d. Vector 2 is the direction of transport during instrumentation. Note shorter ML root (average, 0.75 mm).

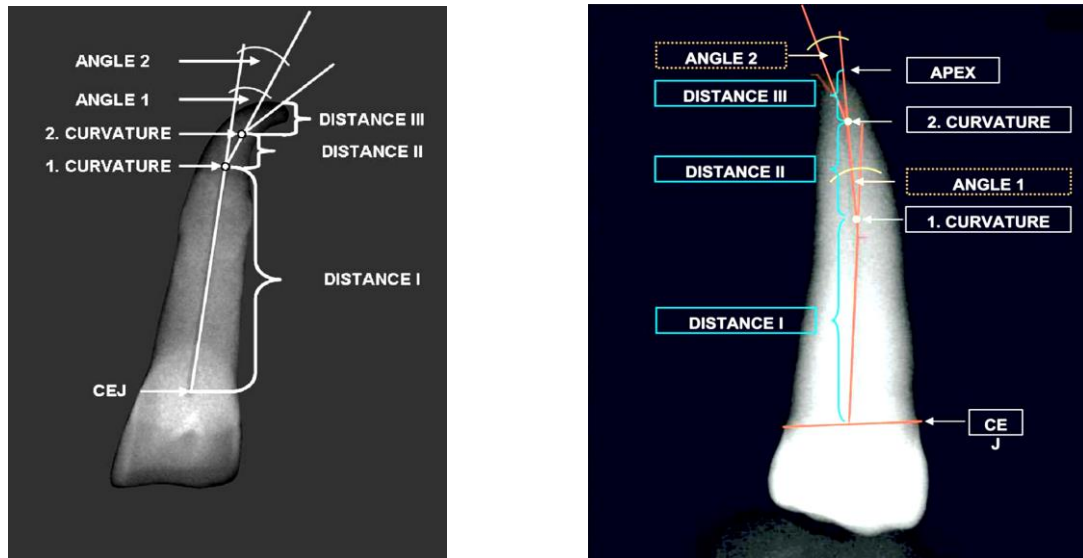


Figure 3. A schematic description of the digitally measured straight distances (tangents), angles, and curvature localization of one selected maxillary lateral incisor (left), maxillary premolar (Right).

A technique for measuring root canal curvature has been stated by Schneider in 1971(19), but modifications of this technique by Pruett *et al*, 1997(20) appropriated into interpretation both the angulation and radius of the curvature. The addition of these two parameters gives a better demonstration of the accurate nature of the root canal faced (Figure 4).

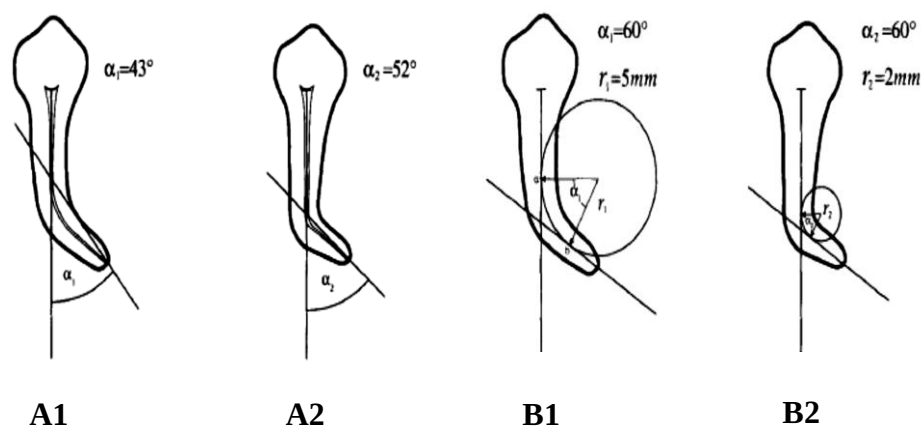


Figure 4. Canal curvature calculation as per Schneider (A1 and A2) and Pruett *et al*. (B1 and B2).

2.4. History of Instruments for Root Canal Therapy

Endodontic procedures have been first reported in the late 17th century. These first efforts involved numerous different original theories and techniques. Edwin Maynard is credited with developing the first endodontic instrument in 1838, which was a filed watch spring(21). Since then, certain endodontic instrument duplications have appeared/disappeared, and the field has progressed until instrument standardization was established in the mid-1960s with the guidance of Green, Ingle, Heuer, and Sampeck(22). Notably, the files produced after these standardization efforts were most possibly still recognized and popular worldwide today: the stainless steel(SS) hand files with a constant 2% taper. Varying lengths of the cutting portion of the active segment of the file, the geometry/metal composition of the wire blank, various shapes were given to the twisted wire (e.g.: reamer, k-file, Hedstrom) and different file tips were combined to create different hand file instruments. The instruments have noted that they are continually being upgraded, and future generation files are being generated more purposefully on a regular basis.

The point of making a scientific discovery that would fundamentally change how the endodontic community undertook the challenge of cleaning and shaping root canal systems was taking folding in the early/mid 1960s, as the standardization of endodontic files and its accompanying handout on the new era of file production were taking folding(23,24). The clinical application of NITINOL (Nickel-Titanium Naval Ordinance Laboratory), first reported in the Orthodontic literature in 1978(25) and then transferred to the manufacturing of endodontic files as a result of Walia *et al*, 1988(3). The introduction of these new NiTi alloys has extended the range of feasible endodontic file designs, created new research opportunities, and increased the rate at which new file designs and manufacturing techniques are developed.

2.4.1. Endodontic instrumentation and its goals

Endodontics is a branch of dentistry concerned with the etiology, diagnosis, prevention, and treatment of apical periodontitis and its ramifications in the body (9). Apical Periodontitis is the infection that endodontists treat for the majority of their careers. To get a beneficial outcome, it should be necessary to consider the etiology and microbiology of this disease(9). Mechanical preparation plays a key role in this situation by physically removing infected dentin and creation space for the irrigation solutions to reach all the parts of the root canal system, especially the apical severely curved area. Besides, when it is accepted that shaping is available to achieve certain goals of treatments, the prepared root canal systems are obturated(12). Most instruments are still designed based on particular clinicians' views rather than produced through an evidence-based manner, and endodontic files have traditionally been created according to scientific designs. The creation of new files, like the creation of composite resins in restorative dentistry, is a quick and market-driven process. With the introduction of new instruments, clinicians may find it challenging to select the file and approach that is most suitable to a certain case. Clinicians must remember that all file systems have advantages and disadvantages. Clinical experience, handling qualities, use safety, and case results, not marketing or the name of the designer, should ultimately decide the fate of a design. Stainless steel and NiTi alloys are the two most common alloys utilized for endodontic equipment nowadays(26). Most manually operated endodontic instruments are fabricated from stainless steel(SS) and because of the inherent stiffness of this material, these instruments have been associated with different clinical mishaps which include ledge, zip formation, perforation of the canal, separation of the instruments(27). Instrument fractures should be less common in a clinician who uses caution when applying stress and follows a regular schedule for discarding instruments after each usage. The design of root canal instruments is often made of nickel-titanium to solve the clinical issues caused by the use of stainless steel (SS) files. This alloy has certain unusual characteristics, including as flexibility and corrosion resistance(26).

2.4.2. Endodontic Hand Instruments

In the past before the 1990s, root canal treatment was performed using classic stainless steel hand instruments of varying lengths, flute designs, and application

procedures. Stainless steel (SS) files are ideal for straight and large root canals, but they are insufficient for difficult root canal architecture, such as severe canal curvatures such as an S-shaped canal or other anatomical abnormalities. When used with a small diameter, the stiffness of these instruments is advantageous for negotiating calcified canals, scouting for canal bifurcation below the canal orifice, attempting to recorrect root canal anatomy after ledges, removing or bypassing existing root canal filling, and removing or bypassing broken instruments. When the tip size of stainless steel files is enlarged, the stiffness of the files gradually increases (and consequent overall bulk of the file). Adequate apical size and canal taper after root canal preparations were still controversial within the field of endodontics(28–32). However, using stainless steel files to increase the apical size of canals during mechanical preparation was more difficult, especially in cases of moderate to severely curved root canals or difficult canal anatomy (e.g., S-shape), and the risk of causing an iatrogenic alteration of the canal was higher. Furthermore, pre-bending file processes were utilized to match the root canal curvature, which took more skills to do because failure to do so might result in ledges, zips, perforations, or even strip perforations, which are deviations from the root canal morphology. Underprepared or unclear root canal anatomy, difficulties making a suitable seal with the root canal filling and sealer, open communication of the root canal with the periodontal ligament space, which led to reinfection, and other clinical issues resulted from these root canal changes. All of these can have unfavorable effects on the prognosis of the root canal treatment and make any subsequent improvements more difficult or impossible(13).

2.4.3. NitTi instruments and Flexibility

The name NiTi referred to a metal alloy made up of nickel and titanium. The Naval Ordnance Laboratory developed these instruments for the space program in the early 1960s(23). The newly developed alloy was called Nitinol, which stands of nickel, titanium, and the initial of the Naval Ordnance Laboratory (-nol). It is composed of approximately 56% by weight of nickel and 44% titanium which provides an equiatomic ratio of nickel and titanium(33). Super-elasticity and shape memory are two of NiTi's unique features. The capacity of an alloy to undergo large deformations and return to its original shape after heating (shape memory property) or after removing the stress (super-

elasticity property) were characterized as shape memory and super-elasticity qualities (34).

The super-elasticity property of the NiTi secures the attention of Dr. Walia's group 1988 (3). They were the first researchers to investigate the possibility of using NiTi in the fabrication of endodontic instruments. They were given a philosophy that NiTi instruments with high flexibility could reduce the chance of occurrence of procedural errors related to the characteristic stiffness of Stainless steel (SS) instruments. In 1988, they fabricated endodontic files in size of #15 from archwire blanks of NiTi and studied their flexibility in bending and their resistance to torsional fracture. These new NiTi files were able to undergo a deformation of more than 90 degrees without having any permanent deformation; this demonstrated the "outstanding elastic flexibility" of the NiTi files. In comparison, permanent deformation of SS files occurred after a 30 degrees bend. These were shown to have 2–3 times the elastic flexibility in bending and torsion, as well as superior resistance to torsional fracturing when compared to similar stainless steel instruments. Their study also showed that NiTi files had a higher torsional resistance with a mean value of $2\frac{1}{2}$ rotations before torsional fracture compared to Stainless steel (SS) files which had a mean value of $1\frac{3}{4}$ rotations. The authors concluded that files made from NiTi showed capacity and could be better suitable designed for the treatment of curved canals in endodontics than Stainless steel (SS) files(3).

In a study in 1995, the authors have compared Lightspeed files (Lightspeed Technology, San Antonio, TX, USA), a new rotary NiTi file system at that time, with Stainless steel (SS) hand files and NiTi hand files in preparation of mesial canals of mandibular molars. In comparison to the other two groups, the Lightspeed system resulted in a more centered and rounder canal preparation with less canal transportation and dentin removal(35). In another study in 1996, the authors have compared the use of NiTi hand files and Stainless steel (SS) hand files by using computed tomography images of canals before instrumentation and after instrumentation. Two different filling techniques were used for the NiTi hand files: quarter turn/pull technique and reaming technique. NiTi files used in conjunction with a reaming approach resulted in less canal transportation, less dentin removal, and better centered and rounder preparations(36). Gluskin *et al.* 2001,

When they compared canals shaped using hand files and Gates Glidden burs to those made using NiTi GT rotary files, they came to similar findings (Dentsply Maillefer, Ballaigues, Switzerland). The use of NiTi rotary instruments resulted in less transportation and higher preservation of tooth structure(37).

From that time, rotary NiTi files have been widely used for the canal instrumentation of the endodontic treatment. To increase the efficiency and safety of these files, manufacture has concentrated on improvements to the file design, file cross-section, and NiTi metallurgy. Different novel concepts in file design include passive and active cutting, radial lands, constant and variable taper, cross-sectional forms, and offset center of rotation. The start of thermomechanically treated NiTi alloy in 2007, which is regarded as a significant step in the history of NiTi files. Heat treatment of NiTi changed the crystalline structure of the alloy, which increased its physical qualities. It resulted in enhanced canal shaping qualities, increased fracture resistance, and fewer clinical errors(38).

Because of its superior corrosion resistance, biocompatibility, shape memory properties, and resistance to cyclic fatigue, NiTi is widely used in medical applications(39).

Young's Modulus of Elasticity was used to determine the material's flexibility. On a stress (shape) Vs strain (deformation) curve, the modulus of elasticity is the slope of the curve, and the elastic limit is the point at which the material returns to its prestress shape once the load is removed. The material then experiences plastic deformation and becomes permanently distorted. As the ultimate tensile strength (UTS) is exceeded, the endpoint of each curve represents mechanical failure or fracture of the instrument. The superelasticity of NiTi instruments was shown to be due to a stress-induced phase transition in the material's crystalline structure. When stressed, the austenitic phase transforms into the martensitic phase, which bends with only a mild force. The metal returns to the austenitic phase once the pressures are released, and the file returns to its previous shape. NiTi's superelasticity allows up to 8% strain to be fully recovered, but in alloys like stainless steel, this ratio is less than 1% with alloys at most(40) (Figure 5).

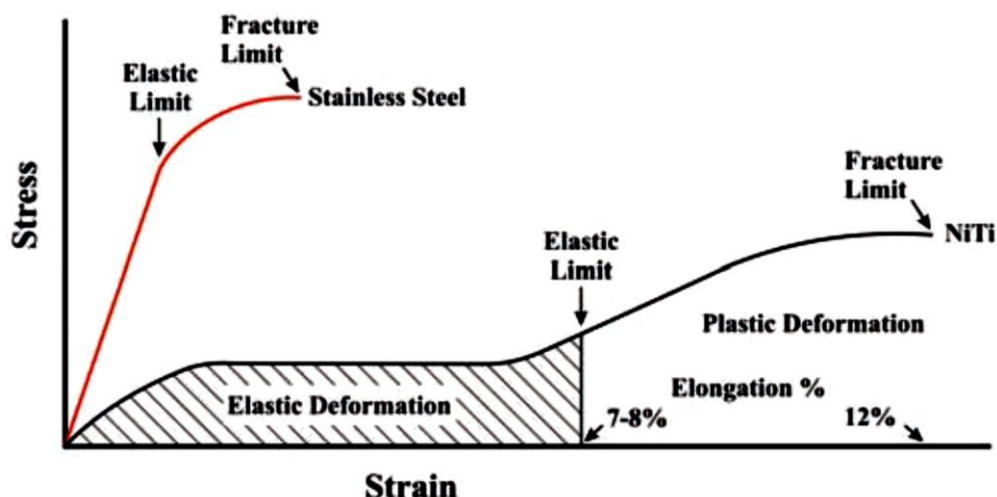


Figure 5. Stress-strain curve: stainless steel (red line) and nickel-titanium (black line). Elastic limit = maximum stress without permanent deformation; fracture limit = stress at which fracture occurs; elongation % refers to the deformation that results from the application of tensile stress, calculated as (change in length/original length) x 100%.

2.4.4. The rationale for Using NiTi Instruments in Endodontic Treatment

As previously stated, stainless steel files' ability to retain the natural curved root canal architecture was diminished and became more challenging as file size increased. Many of the clinical difficulties related with the use of more conventional endodontic stainless steel (SS) files and the procedures utilized with them have been resolved with the introduction of NiTi alloys into the field of endodontics. In the mechanical shaping of root canals, NiTi files have dramatically reduced the quantity and severity of iatrogenic errors(41,42). The special features of NiTi files' superelasticity would improve cutting efficiency, save time, and reduce clinician fatigue. NiTi files' superelastic qualities allow for a safe way to shaping a canal with a continuous taper, following the canal anatomy with a bigger file taper while preserving the root canal's original form. NiTi files were commonly utilized with a constant taper of 2%, 4%, 6%, or more, as well as with varied taper throughout the length of the same file. These files can have a continuous rotational kinematic motion, but a reciprocating motion has lately been effectively added. To far, no studies have shown a difference in clinical success when using stainless steel (SS) hand files, rotary NiTi files, or reciprocating NiTi files for root canal instrumentation(38,41). Subsequently, the skill level of the clinician may become

efficient with the use of NiTi instruments while decreasing the potential for an iatrogenic mishap during shaping the root canal(43,44).

2.4.5. Heat Treatment of Rotary NiTi Instruments

As previously stated, the NiTi alloy utilized in endodontic instruments has around 56 wt% nickel and 44 wt% titanium, resulting in an atomic ratio of almost one-to-one (equiatomic)(33). The temperature-dependent crystal structures of this equiatomic NiTi alloy may be found in two distinct form named austenite (high-temperature or parent phase, with a cubic B2 crystal structure) and martensite phase (low-temperature phase, with a monoclinic B19' crystal structure) (39,45) (Figure 6, and Table 1), and possesses typical characteristics which are superelasticity (SE) and shape memory effect (SME) (Table 2). The austenite-to-martensite transition (martensitic transformation), which can be caused by stress or temperature, results in these features (Figure 7).

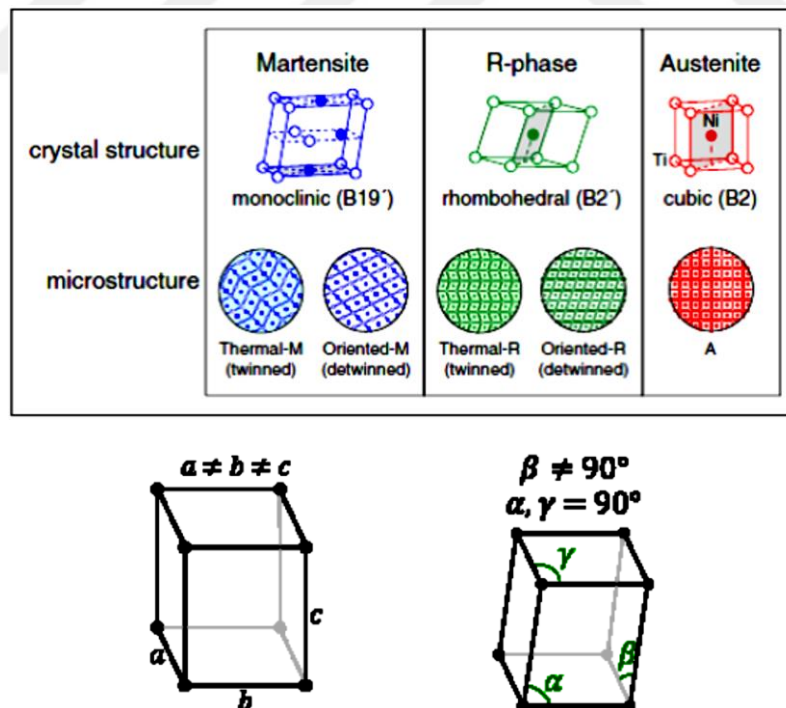


Figure 6. Schematics of crystal structures and microstructures of martensite, R- phase, and austenite.

Table 1. Crystallographic structure of individual phases.

S.NO	Phase	Crystal classification	Designation	Edge length	Interaxial angle
1.	Austenite	Cubic	B2	$a=b=c$	$\alpha=\beta=\gamma=90^0$
2.	R phase	Rhombohedral	B2'	$a=b=c$	$\alpha=\beta=\gamma\neq 90^0$
3.	Martensite	Orthorhombic	B19	$a\neq b\neq c$	$\alpha=\beta=\gamma=90^0$
4.	Detwinned	Monoclinic	B19'	$a\neq b\neq c$	$\alpha=\gamma=90^0\neq\beta$

Table 2. Definition of the martensitic transformations.

Superelasticity (SE)= Pseudoelasticity	Complete recoverable elastic deformation up to 8% strain due to phase transformation between stable austenite and stress-induced martensite phase (Figure 7).
Shape memory effect (SME)	The ability of deformed NiTi instrument to recover its original shape once heated due to phase transformation of stable deformed martensite to stable austenite phase (Figure 7).

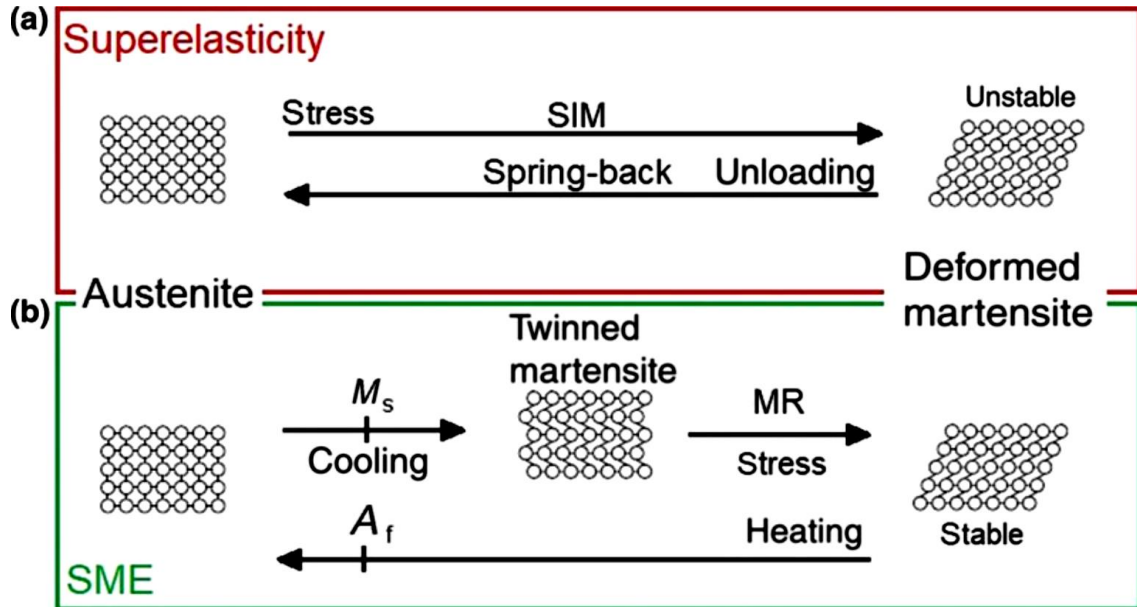


Figure 7. Martensitic transformations. (a) Superelasticity (SE) at ambient temperature above the austenite finish temperature (A_f). (b) Shape memory effect (SME). For the martensite reorientation (MR), less stress is required than for stress-induced martensite (SIM) transformation. (M_s = martensite start temperature).

Under certain circumstances (e.g. aging at temperatures around 400 °C to foundation the precipitation of Ti_3Ni_4 phase, the exchange of a third element (iron, aluminum) or heat treatment after cold employed to make repositioned dislocation structures), a rhombohedral distorted phase (R-phase) may appear before the transformation to martensite(46). This R-phase transformation was established as a martensitic transformation itself that competes with the subsequent martensitic transformation(47). The stress happening during this cubic (austenite) to rhombohedral (R-phase), respectively, monoclinic (martensite) lattice transformation was released by the twinning of the new phase structure (twinned R-phase or martensite) (Figure 7). Martensite phase exhibits a lower elastic modulus (about 30–40 GPa) than austenite phase (about 80–90 GPa)(48), and Young's Modulus of the R-phase is lower than that of Martensite phase, and therefore, an instrument with the R-phase transformation could be more flexible(49).

The phase composition of the NiTi alloy and, as a consequence, its mechanical characteristics were influenced by the ambient temperature (air temperature), as well as whether the alloy was cooled or heated to this temperature(Figure 8). The alloy is in an

austenitic phase if the temperature is above the austenite finish temperature (A_f), and the qualities of this phase are stiff, hard, and have superior superelastic characteristics(50). The NiTi alloy is in the martensitic phase if the temperature is below the martensite finish temperature (M_f), and the qualities of this phase are soft, ductile, readily deformable, and exhibit the shape memory effect(50). When compared to austenite, martensite has a higher cycle fatigue resistance due to the reorientation capability of the twinned phase structure(45,51).

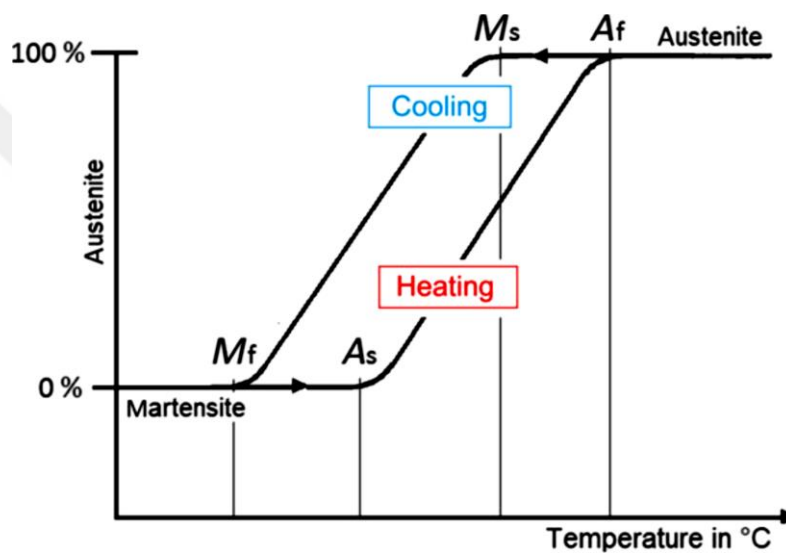


Figure 8. Temperature hysteresis diagram of NiTi alloy. (M_s) martensite start temperature, (M_f) martensite finish temperature, (A_s) austenite start temperature, (A_f) austenite finish temperature.

2.4.6. NiTi Wire Alloys

Endodontic instruments made of NiTi alloys can be classified into those that mostly include the austenite phase (austenitic: conventional NiTi, M-Wire, R-Phase) and those that mostly include the martensite phase (martensitic: CM Wire, Gold, and Blue heat-treated NiTi)(52) (Table 3).

Table 3. Overview of NiTi alloy used for the manufacture of endodontic instruments.

Alloy	Phase composition/ properties	NiTi system
Conventional NiTi alloy	Austenitic: Superelastic	Mtwo OneShape Profile Protaper Universal
Electropolishing		RaCe, BioRaCe, iRace F360, F6 Skytaper
R- Phase	Austenitic: Superelastic Twisted	Twisted File Twisted File Adaptive K3XF (not twisted)
M- Wire	Austenitic with small amounts of R-phase and martensite: Superelastic Two stages stress-induced transformation through R – phase	Profile Vortex Profile GT Series X Protaper Next Reciproc WaveOne
CM wire and Gold heat-treated And Blue heated treated	Martensitic with varying amounts of austenite and R- phase: Controlled memory effect Deformable, pseudoplastic Shape memory effect Superior flexibility Enhanced cyclic fatigue resistance The greater angle of rotation at the fracture Lower maximum torque	Hyflex CM, Hyflex EDM THYPOON Infinite Flex NiTi Files V – Taper 2H OneCurve, EdgeFile Protaper Gold WaveOne Gold Profile Vortex Blue Reciproc Blue
MaxWire	Martensitic (20 ⁰), austenitic (35 ⁰): Shape memory effect Superelastic	XP – Endo Shaper XP – Endo Finisher

2.4.6.1. Austenitic NiTi alloy

To apply the superelasticity of NiTi alloy, NiTi endodontic instruments should predominantly be made of the austenite phase(50). Stress caused austenite to convert into martensite (e.g. insert of the instrument into a curved root canal). Stress-induced martensite (SIM) transformation is the name for this phenomenon(Figure 7). The transformation of the austenitic cubic crystal lattice to the martensitic monoclinic crystal lattice permits a complete recovery of the deformation up to 8% strain(33). Because the stress-induced martensitic state was not stable at the current temperature, unloading the endodontic instrument (e.g., withdrawing an instrument from a curved root canal) causes retransformation to the austenite phase, and the endodontic instrument springs back to its

previous shape(Figure 7). In addition to superelasticity, NiTi alloy owns a lower elastic modulus compared with stainless steel which resultant high flexibility of NiTi endodontic instruments(53).

2.4.6.1.A. Conventional NiTi alloy

Conventional NiTi endodontic instruments include around 56 wt% nickel and 44 wt% titanium, with the austenite phase accounting for the majority of the material and possessing its unique superelastic characteristics(33). The austenite finish temperature is beneath the body temperature(54). The manufacture of these instruments was ground rather than twisted(33). The grinding process might cause faults on the surface of NiTi instruments, which might have a detrimental impact on fracture resistance, cutting efficiency, and corrosion resistance(33).

2.4.6.1.B. Electropolishing

Electropolishing is a surface finishing method for metal workpieces that involves the controlled electrochemical removal of surface material to provide a smoother, higher-gloss surface. An electropolishing procedure is utilized during the engineering of NiTi endodontic instruments to eliminate surface imperfections, fractures, and residual stress that may have developed during the previous grinding process to increase fracture resistance, cutting efficiency, and corrosion resistance(55–57).

2.4.6.1.C. M wire technology

M-Wire was created in 2007 to increase the flexibility and cyclic fatigue resistance of a newly discovered NiTi alloy. The Nitinol composition of M wire 55.8 ± 1.5 wt% nickel (Ni), 44.2 ± 1.5 wt% titanium (Ti), and trace elements less than 1 wt%(58). The austenite finish temperature of M-Wire around $43\text{--}50^{\circ}\text{C}$ (59,60), and subsequently well above than A_f of conventional NiTi and body temperature, thus demonstrating that M-Wire was not completely composed of austenite under clinical conditions. At body temperature, M-Wire comprises austenite phase with tiny quantities of martensite and R-

phase, according to several metallurgical laboratory tests (e.g. DSC, XRD, and SEM)(60,61). Also, M-Wire maintains a superelastic state(60). Furthermore, M-Wire is more flexible than conventionally manufactured NiTi wire, and the reason for this is because martensite and R-phase elastic moduli are smaller than austenite's. Additionally, Pereira *et al*(54,61). Found that the stress-strain curve of M-Wire exhibits a characteristic yielding phenomenon(Figure 9), indicating that a stress-induced R-phase formation occurs before stress-induced martensite (SIM) transformation. As a result, M-Wire has a lower initial elastic modulus than conventional NiTi, as seen by a lower initial inclination of the loading curve(54,61). In addition, the stress-strain diagram shows that M-Wire needed less stress to initiate martensite transition than conventional NiTi. Finally, greater fatigue resistance of M-wire might be explained by increased fatigue-crack initiation resistance due to better reorientation ability of the martensitic variants(62) (Figure 10).

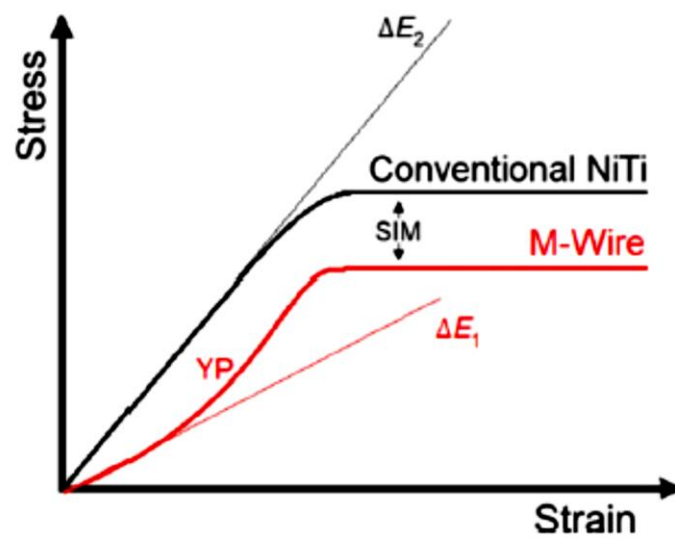


Figure 9. Schematic stress-strain diagram of conventional NiTi (black) and M-Wire (red) displaying the yielding phenomenon (YP) resulting in a lower initial elastic modulus of M-Wire (ΔE_1) compared with conventional NiTi (ΔE_2). The stress plateau occurs due to stress-induced martensite (SIM) transformation.

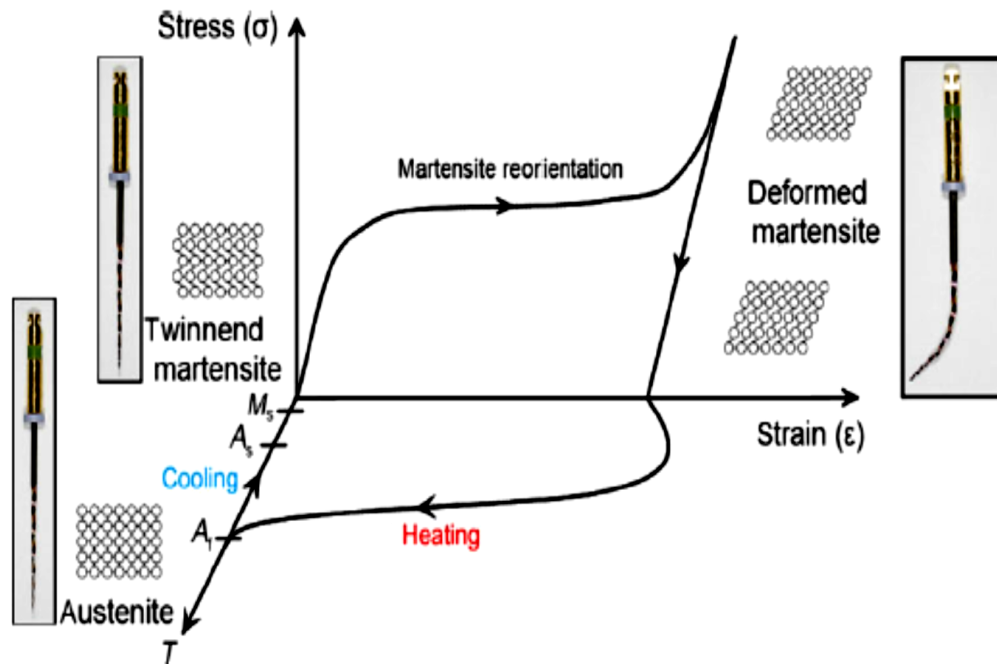


Figure 10. Stress-strain-temperature diagram showing the shape memory effect of martensitic NiTi instruments (e.g. Hyflex CM). The stress-plateau occurs due to martensite reorientation (MR).

2.4.6.1.D. R - phase wire

After a short introduction of M-Wire in 2008, SybronEndo (Orange, CA, USA) developed a new manufacturing technique to create the Twisted File rotating NiTi system (TF). Three new processes are included in the TF production system: Heat treatment in the R-phase, metal wire twisting, and specific surface conditioning(63). The twisting process begins with a raw NiTi wire in the austenitic condition being transformed into R-phase using a patented thermal method. R-phase has a reduced shear modulus and a transition strain that is less than a tenth of that of martensite. As a result, in the R-phase, less stress is required to create a plastic deformation, allowing the twisting process to continue(64). After twisting, TF converted back to austenite state by added thermal procedures to maintain its new shape(64). Two more NiTi systems with patented R-phase technology have also been released (K3XF, TF Adaptive; Sybron Endo). The K3XF instruments were made using a standard grinding method with post-machining R-phase heat treatment, as opposed to TF and TF Adaptive (TFA). The twisted TFA instruments are employed in a novel adaptive motion technique that allows the file to rotate or

reciprocate depending on intracanal torsional pressures. As a result, as previously stated, R-phase instruments demonstrated higher resistance to cycle fatigue(65), for torsional fracture have a greater angle of deflection at failure but lower torque compared with M-Wire and conventional NiTi instrument(66), superior flexibility(67), and allow for more centered canal preparation with less transportation than conventional NiTi rotary instruments(68).

2.4.6.2. Martensitic NiTi alloy

The martensite NiTi alloy has softer and more ductile characteristics than austenite. Furthermore, it is readily deformable and has a shape memory effect when heated. The martensite phase's fatigue-crack development resistance was found to be greater than that of stable austenite(69). The martensite phase was considered with favorable fatigue resistance because of a hybrid (austenite-to-martensite) phase composition with a certain proportion of martensite(45). For those reasons, the transformation temperatures of the NiTi alloy could be raised (e.g. by thermomechanical treatment). Once the heating, the austenite finishes temperature NiTi endodontic instruments are started and mainly consist of NiTi instruments at this stage is the austenite phase. While on cooling, a sequential austenite-to-martensite transformation occurs below the martensite start temperature. The stress occurring during this cubic (B2) to monoclinic (B19') lattice transformation was released by the twinning of the developed martensite (twinned martensite) without macroscopic form changes of the endodontic instrument. Twinned martensite can be plastically deformed under stress, leading to detwinning of the lattice structure (deformed martensite). This transformation from twinned to deformed martensite is called martensite reorientation (MR). Similar to SIM, the MR enables deformation of up to 8% strain without a significant increase in stress(52,70). Heating the deformed instrument over the austenite finish temperature (e.g. autoclaving) causes it to return to the primary austenitic condition, allowing it to restore its original shape(Figure 10). As a consequence, martensitic instruments are pseudoplastic and exhibit shape memory when heated.

2.4.6.2.A. CM Wire

Controlled memory (CM) Wire, the first thermomechanically treated NiTi endodontic alloy lacking superelastic characteristics at room or body temperature, was released in 2010(71). Because of modified phase compositions, CM Wire instruments can be deformed because of the reorientation of the martensite variants(45). CM Wire instruments, unlike austenitic NiTi files, do not incline to completely straighten during the preparation of curved root canals (Figure 11). According to the manufacturer, this controlled memory effect was supposed to reduce the incidence of preparation errors(6).

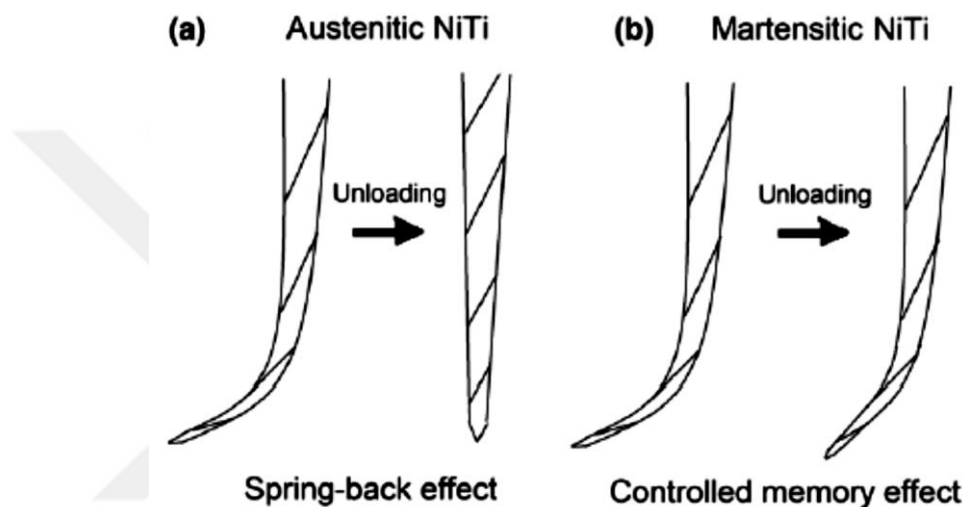


Figure 11. (a) Spring-back effect of austenitic NiTi alloys (b) controlled memory effect of martensitic NiTi alloys.

DSC analysis (Differential scanning calorimetry) showed that the austenite finish temperature of CM Wire instruments was above intracanal temperature (around 47–55⁰ C)(51). Iacono *et al.* explained an unused Hyflex CM instruments display Af temperatures around 32–37⁰ C, whilst the Af temperature for used Hyflex CM instruments is about 54–61⁰ C(72). As a result, XRD study (X-ray diffraction) of Hyflex CM and Typhoon CM (Clinician's Choice Dental Products, New Milford, CT, USA) revealed that at room temperature, both new and used CM Wire instruments were a mixture of austenite and martensite structure with tiny quantities of the R-phase(51,72).

CM Wire instruments had superior flexibility than M-Wire and conventional NiTi instruments(73,74). The increased flexibility was attributed to the fact that the critical stress required to induce martensite reorientation (twinned to deformed martensite) in

martensitic instruments was significantly less than the critical stress required to induce SIM transformation (austenite to deformed martensite) in austenitic instruments(71) (Figure 7). Cutting efficiency has been shown to be harmed by more flexibility. Hyflex CM instruments, when compared to electropolished and conventional NiTi instruments, offer a higher cutting efficiency in lateral motion(75). Lastly, CM Wire instruments have significantly improved cyclic fatigue resistance compared to M-Wire and conventional NiTi instruments(76).

2.4.6.2.B. Electrical Discharge Machining (Hyflex EDM)

Hyflex EDM was introduced by Coltene/Whaledent and manufactured from CM Wire. Hyflex EDM was the first endodontic instrument manufactured through an electrical discharge machining (EDM) procedure(77). According to the manufacturer, this novel machining procedure would harden the NiTi file's surface, resulting in increased fracture resistance and cutting efficiency(78).

EDM was a recognized noncontact machining procedure that permits precise material removal through pulsated electrical discharge(79,80). Both the machining tool (electrode) and the workpiece must be electrically conductive for EDM to work(80). The machining tool is pushed towards the workpiece while embedded in a dielectric liquid until the gap is narrow enough for the applied voltage to ionize the dielectric liquid(52,79). Small particles from the workpiece evaporate as a result of the spark, which resolidify in the dielectric liquid and then are flushed away (79) (Figure 12). Because EDM does not need direct contact with the workpiece, there is no risk of mechanical stress, as there is with conventional grinding(81). Even after many clinical uses, EDM generates a crater-like surface that does not compromise the instrument's integrity (77). Uslu *et al* 2018, the surface topographies of undamaged Hyflex CM and EDM files were examined before and after root canal preparation. Using three-dimensional optical profilometry, Although there were no significant increases in surface roughness in the Hyflex EDM group, after the preparation of extremely curved root canals, Hyflex CM had much larger surface alterations than Hyflex EDM(82).

The transformation temperatures M_s , A_s , and A_f for new Hyflex EDM instruments are higher than for Hyflex CM, demonstrating a changed phase composition(72). The microstructure of Hyflex EDM revealed lenticular grains (supposed to be martensite) interchanging with big flat grains (supposed to be austenite) according to optical metallographic examination(77). On the other hand, Hyflex EDM has martensite and significant quantities of R-phase, whereas Hyflex CM is a combination of martensite and austenite, according to XRD examination(72). The absence of austenite in Hyflex EDM files may perhaps by its increased austenite start temperature ($A_s \approx 42^0\text{ C}$) compared with Hyflex CM ($A_s \approx 21^0\text{ C}$) which leads to prevent the formation of austenite at either room or body temperature(72).

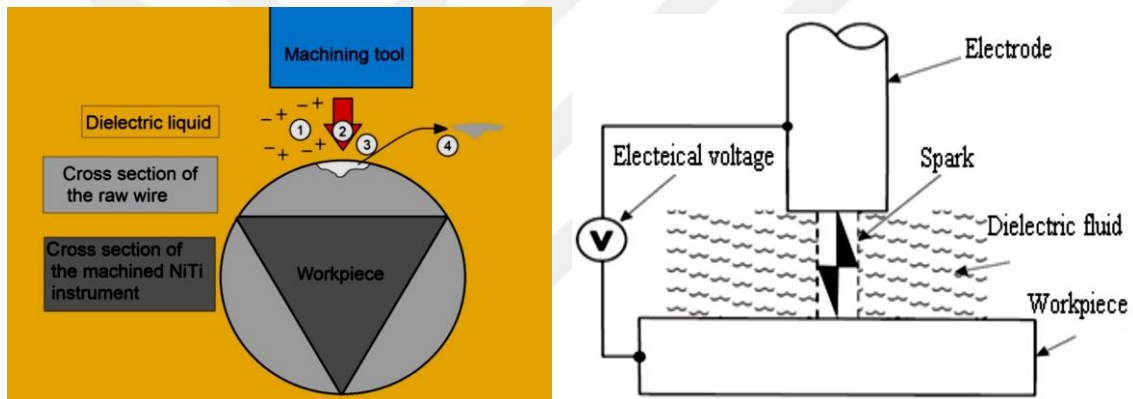


Figure 12. Electrical discharge machining (left). (1) Ionization of the dielectric liquid (2) Spark (3) Vaporization of a small particle (4) Resolidification. Basic components of EDM (Right).

As previously stated, as compared to Hyflex CM, M-Wire, and conventional NiTi instruments, Hyflex EDM demonstrates considerably higher cycle fatigue resistance and centered root canal preparation while maintaining the original root canal morphology(83). The flexibility of Hyflex EDM was similar to other CM Wire instruments(72). Hyflex EDM has been stated to create a centered root canal preparation, concerning the original root canal anatomy(84). Also, Hyflex EDM instruments exposed a greater angle of rotation at the fracture but lower torque than M Wire instruments(83). Furthermore, Hyflex EDM exhibited lower austenite phase values but had higher hardness than Hyflex CM(72).

2.4.6.2.C. Gold and Blue Heat – Treated Instruments

ProFile Vortex Blue, introduced by Dentsply Tulsa Dental (Tulsa, OK, USA) in 2011, is the first endodontic instrument with a blue color. Its name comes from an unique blue color. Two Gold and two Blue heat-treated NiTi systems are now available. Two of them are used in a rotational motion (ProFile Vortex Blue; ProTaper Gold, Dentsply Sirona Endodontics), while the other two are used in a reciprocating motion (Reciproc Blue, VDW; WaveOne Gold, Dentsply Sirona Endodontics). These instruments may also be deformed and also have a controlled memory effect(85). The primary difference between CM Wire and Gold heat-treated instruments is that Blue heat-treated instruments are first ground and then subjected to a proprietary post-machining heat treatment(73).

During post-machining heat treatment for Vortex Blue instruments, these files took on a characteristic blue color, which was caused by a visible titanium oxide layer(86). The austenite finish temperature for Vortex Blue was closed to body temperature (38.5⁰ C), whilst the martensite starts temperature is approximately 31⁰ C(87). Blue heat-treated instruments showed less Vickers surface hardness than M-Wire instruments(88,89). The controlled memory behavior of Blue heat-treated files, which contain more stable martensite than M-Wire, predisposes to a softer, more ductile NiTi alloy. Also the gold color that results from a surface coating on gold heat-treated instruments. The austenite finish temperature of ProTaper Gold was revealed to be almost 50⁰ C using DSC analysis(90). As a result, under clinical conditions, these instruments generally contain martensite or R- phase. Due to proprietary processing of post machining heat treatment, all Gold and Blue heat-treated files showed greater flexibility and fatigue resistance compared to conventional NiTi and M-Wire instruments, which also enhanced torque strength and reduced shape memory of the files(88,90).

2.4.6.3. Martensite-Austenite-Electropolish

Currently, FKG Dentaire has introduced Max- Wire (Martensite-Austenite-electropolish –file X), a proprietary thermomechanically treated NiTi alloy that is the first endodontic NiTi alloy with both shape memory and superelasticity qualities in clinical

use. Until now, only the XP-endo Shaper and XP-endo Finisher were available from them (both FKG Dentaire). These instruments are relatively straight in their M-phase (martensitic state) at ambient temperature, but they convert into a curved shape when subjected to intracanal temperature due to a phase transformation to A-phase (austenitic state)(8). Thus, when placed into the root canal, these instruments have a shape memory effect (M-phase to A-phase) and are superelastic during preparation. The file's curled design is recommended because it allows for the preparation of complicated root canal morphologies while also allowing for familiarity with canal irregularities.

The XP-endoShaper showed considerably increased cyclic fatigue resistance compared with Hyflex CM, Vortex Blue, and iRaCe (FKG Dentaire)(91,92), but had less torsional resistance compared with Vortex (Dentsply Tulsa) and FlexMaster (VDW) (92,93). The XP-endoShaper instrument's cyclic and torsional resistance are greatly influenced by its low taper design (0.01). That instance, a smaller diameter of NiTi rotary instruments enhances cyclic fatigue and decreases torsional resistance(94). There were no research on the transition temperatures, phase composition, or flexibility of MaxWire instruments available at the time.

2.5. Types of Fatigue Failure of Rotary NiTi Instruments

The endodontic file was subject to fracture in one of two modes during canal instrumentation: torsional fracture or cyclic (flexural) fatigue fracture(95). Despite the fact that this study is focused on cyclic failure, torsional fatigue may play a role in endodontic instrument fracture and hence requires explanation.

Torsional stress was generated when the tip of a rotary file gets locked in the canal and the other part continues to rotate. Once the torsional stress goes beyond the elastic limit of the metal, a torsional (or shear) fracture occurs. This type of fracture was attended by longitudinally visible plastic deformation of the file near the fracture line(95). But, in some cases also happen without any signs of plastic deformation(96).

Cyclic fatigue fracture was connected with the use of rotary files in a curved canal. A rotating file in a curved canal generates repetitive and alternating zones of compression and tension along with the file, which causes metal fatigue. Cyclic fatigue failure occurs as a result of stress accumulation in a specific area of an endodontic file used in rotation inside a curved root canal. Within the apex of the curved area of the root canal, the corresponding segment of the endodontic file endures repetitive stress due to the compression of the file on the internal side of the curvature and tension of the file on the external side of the curvature. The cyclic fatigue of the file is caused by the accumulation of metal fatigue. Cyclic fatigue unlike torsional fracture, occurs without any obvious faults on the file's longitudinal surface(96).

Sattapan *et al* 2000(95). A total of 378 discarded endodontic Quantec files (Quantec Series 2000, Tycom Corp, Irvine, CA) after normal use from a specialist endodontic practice over 6 months were analyzed. Nearly half of the files had some apparent defect (macroscopic); 21% were fractured, and 28% had other defects that were not broken. According to the features of the defects discovered, fractured files can be divided into two groups. In 55.7% of all broken files, torsional fracture occurred, whereas flexural fatigue occurred in 44.3%. The findings revealed that excessive apical force during instrumentation might produce torsional failure, which occurs more commonly than flexural fatigue, which can occur in curved canals. The torsional fracture was accompanied by defects consisting of unwinding, reverse winding, reverse winding with tightening of the spirals, or a combination of these defects, according to the defect characteristics. On the other hand, cyclic fatigue fracture was characterized by a sharp break with no obvious faults(95).

Parashos P *et al* 2004(97). Analyzed discarded rotary nickel-titanium instruments gotten from 14 endodontists in four countries. A total of 7,159 instruments were examined for the presence of defects. They examined the defect according to Sattapan criteria(95) and founded deformation (unwinding) occurred in 12% of instruments and fractures in 5% (1.5% torsional, 3.5% flexural). The operator had the biggest influence on defect rates, which might be attributed to clinical skill or a conscious decision to use instruments

a certain number of times or until defects were visible. Instrument design considerations also had an impact on the defect rate, but to a lesser extent(97).

Peng B *et al* 2005(98). They examined discarded ProTaper (Dentsply Maillefer) S1 instruments from the endodontic clinic of a dental school above a period of 17 months under a scanning electron microscope with longitudinal views. A total of 122 S1 instruments was examined and revealed 23% were fractured (27/122). According to the criteria set by Sattapan *et al*(95), Almost all files were broken due to cyclic fatigue (25/27). A torsional fracture was found in just two of the files. Because the S1 instrument has a variable taper, it decreases the taper-lock effect and hence the torsional stress on the file(98).

It was mentioned before in the same study(98), but published later with other ideas by Cheung *et al* 2005(99), that the fractographic surface of these same instruments was examined under the scanning electron microscope. The fractured surface of a cyclic fatigue fracture would include characteristic "fatigue striations" or "beach markings" as well as a dimpled region. A torsional fracture, on the other hand, would be distinguished by the absence of fatigue striations, the existence of concentric rubbing or abrasion marks, and the existence of skewed dimple regions on the fractured surface. These parameters were used to re-determine the kind of fracture. As a result, the authors came to the conclusion that a longitudinal study of a fractured file was insufficient to establish the kind of fracture, and that fractographic study using a scanning electron microscope was required(99).

The cycle fatigue failure begins microscopically near the file's edge, at a zone of concentrated stress. Defects in the NiTi blank's cutting edge, such as a bubble, serve as a concentration site for fracture initiation(96). Continued compression-tension cycles on this freshly initiated crack advance slowly and gradually toward the file's core. The chevron pattern is used to describe this location. The proportion of the intact file that maintains its integrity decreases as the crack grows. This remaining file structure can no longer sustain these stresses at a crucial spot, and fast crack propagation occurs, resulting in the file's failure(96).

Fractographic examination under a scanning electron microscope (SEM) of fractured file fragments was beneficial for determining which fracture mode occurred. High magnification SEM examination of file fragment fractured due to cyclic fatigue typically show striations in the crack initiation/slow propagation zone and a dimpled area (or beach mark) in the rapid fracture propagation area (Figure 13). Torsional fracture mode was easily distinguished from cyclic fatigue failure. Torsional file fracture habitually but not always shows signs of plastic deformation when viewed laterally and, under SEM, was revealed itself with a circular pattern of striae resembling grooves on a vinyl record due to the shear stress of the coronal file fragment rotating against its immobile apical portion(96).

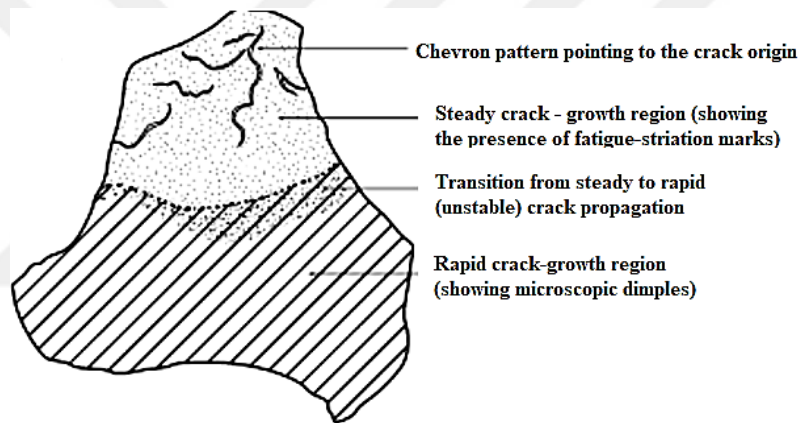


Figure 13. Schematic drawing of various regions for cyclic fatigue failure.

2.6. Mechanism of Cyclic Fatigue Failure

The initiation of crack formation is strongly influenced by ground processes. This is because the mechanical grinding process causes areas of work hardening and brittleness on the file surface, which are more prone to cracking when stresses are concentrated there. During processing, the presence of inclusions or defects in the alloy or on the surface causes zones of weakness along which cracks might grow(100).

The position and distribution of stress in a cycling instrument with clear material qualities, geometry, and load conditions is determined using finite element analysis (FEA). The fracture point was near to the area of maximum stress, according to FEA, and the standard deviation between the estimated and real fracture points reduces as curvature increases(101).

Crack propagation in austenite with just one crystalline form appears to occur through a few fatigue cracks that tend to nucleate (start) in the SA (Stable Austenite) wire and propagate in a straight line without branching. Because of the numerous (sixteen) martensite variants, crack propagation in martensite occurs through multiple highly branched cracks, resulting in reduced fatigue stress and a prolonged fatigue life. Furthermore, stress-induced martensite (SIM) tends to be restricted to a smaller volume portion than martensite reorientation, hence SIM was linked to higher stress levels(102).

It has been reported that the material with more ductile properties, the greater its resistance to cyclic fatigue(103).

2.7. Factors Influencing File Separation

Operator skill/experience, instrumentation method, torque, and speed, number of uses, instrument design, the anatomic configuration of the canals, metallurgy, and the number of sterilizing cycles have all been linked to the separation of NiTi instruments, etc.

2.7.1. Operator skill/experience

The operator's skill is the most important factor in instrument failure. When all other variables (instrument speed and sequence, canal morphology) were kept constant, the operator was shown to be the most critical determinant in file separation(97). Each rotary NiTi system has a 'learning curve,' recognizing the importance of good training and early supervision in the use of NiTi endodontic systems, as these instruments are prone to fracture if misused or overused(95).

2.7.2. Impact of Instrumentation Technique

It has been suggested that using a crown-down instrumentation technique (enlarging the coronal aspect of the canal before apical preparation) and creating a manual glide path (manually preparing the canals with an SS file to working length before rotary NiTi instrumentation) can reduce the rate of instrument fracture(104,105). Those techniques aid in the reduction of instrument "taper lock" or "instrument jamming," which has been linked to torsional fractures. Crown-down procedures decrease torsional stresses, which are especially common in smaller instruments(106), and a glide path limits the amount of torque applied to the instrument, preventing shear fracture(104). They also recommend using stainless steel hand files to prepare the apical third of curved canals before using rotary files to reduce file separation(104).

2.7.3. Impact of Torque Factor

Torque-controlled electric motors were recommended for use with rotary NiTi systems. When an endodontic motor is set to lower torque levels, the CFR of NiTi rotary instruments increases(107). The possible explanation for that is the mechanical stress on NiTi rotary instruments is also proportional to motor torque. If a high-torque motor is set, once the instrument-specific torque limit is exceeded, thus increasing the mechanical stress and the risks of plastic deformation/intracanal separation(107). If the torque is adjusted just below each instrument's elasticity limit, the mechanical stress is decreased, and the danger of plastic deformation and separation is minimized to a level considerably below what was previously achievable(107). On the contrary, the authors of another study said that high torque endodontic motors are recommended for better shaping(108). And their opinion that the endodontic motor routinely used auto-reverse at low torque, but auto-reverse was never activated at high torque, resulting in this significant and consistent variation in instrument life. Auto-reverse isn't entirely a bad thing, especially for instruments that require a low maximum torque(108).

2.7.4. Impact of Speed Factor

The influence of rotational speed on fracture is still controversial, with some research claiming that rotational speed has no effect on fracture occurrence(44). Other research, on the other hand, found the contrary(109). And those difficulties are arises when comparing these studies, as methods of testing, instrument types, and operator experience was different in each study. Operator experience and knowledge of dental anatomy were probably more significant variables in predicting the risk of instrument separation than file design. Yared *et al* 2002, identified the hands of experienced operators as a critical component in safe instrument handling, and they recommended inexperienced operators to use lower rpm settings(44). For these reasons, most manufacturers recommend keeping to a defined set of revolutions per minute (rpm) while using rotary NiTi instruments. Furthermore, the following hypotheses may explain for those findings: the first is that the time to failure dropped dramatically as the degrees of curvature or rotational speeds increased (110). Second, the tactile sensation of binding may prevent torsion or brittle type fractures at a slower rpm, permitting withdrawal of a file from a canal before exceeding the alloy's elastic limit. A proper rotating speed and constant pecking action in the root canals were suggested to avoid endodontic instruments from separating(110).

2.7.5. Tooth type, Canal curvature, and Radius Factors

Cyclic fatigue testing of rotary NiTi files has established that fracture happens at the point of maximum flexure, which corresponds to the point of greatest curvature within simulated root canals. The angle of curvature was described by Schneider *et al* 1971 as the angle formed by a first line drawn parallel to the canal's long axis and a second line drawn from the apical foramen to the point where the canal began to leave the tooth's long axis(19) (Figure 4). He classified a canal as straight if the angle was at or less than 5 degrees, moderate if the angle was 10 to 20 degrees, and severe if the angle was between 25 and 70 degrees(19). Thus, increases in the angle of curvature and the radius of curvature decreases those leads to a reduced number of cycles to file fracture(111,112). Furthermore, one of the major issues is that as the angle of canal curvature increases, discrepancies between the canal axis and the axis of the measuring devices also increase(113). In molar teeth, the radius of canal curvature was often reduced, reducing

the instrument's capacity to resist torsional stresses. This is also consistent with clinicians' findings that NiTi files fracture more easily when the tip binds in an acutely curved canal(114).

This has been observed clinically where instrument fracture was significantly greater (up to 2.9 ×) in molars than in premolars(115). Furthermore, the probability of fracturing an instrument in the mesiobuccal canal of a maxillary molar was three times greater than the distobuccal canal; similarly, the probability of fracturing a file in the mesiobuccal canal of a mandibular molar (recognized for their greater curvature) was greater than the mesiolingual canal(115).

This was supported by clinical research that the majority of instruments fractured in the apical third of the canal, which was the area with the greatest curvature and the smallest diameter(115). The chances of separating a file were 33 times higher in the apical regions than in the coronal-third and 6 times higher in the middle-third of the root (115).

2.7.6. Effect of Sterilization and Irrigation

On the subject of the influence of sterilization on NiTi endodontic instruments, there are conflicting results in the literature. According to several investigations, evidence of crack start and propagation, an increase in the depth of surface imperfections, and a reduction in cutting effectiveness have been seen when NiTi instruments have been exposed to several sterilization/autoclave cycles(116,117). Other researchers have discovered that heat sterilization, even up to ten times, and clinical usage in the presence of NaOCl did not result in a reduction in the number of rotations to fracture of NiTi file(118–120). On the contrary, the cyclic fatigue resistance of HyFlex CM and K3XF extended after autoclave sterilization(121).

Finally, it has been stated that NaOCl was unlikely to cause corrosion of NiTi instruments when immersed in diluted NaOCl for a short period of time, but using a high concentration of NaOCl for longer periods of time (overnight 18h) may result in corrosion

effects, and thus its use did not significantly reduce the prevalence of fracture or the number of revolutions to cause flexural fatigue of NiTi(122,123).

2.7.7. Number of Uses

Many studies reported that NiTi instrument failure was influenced more by how they were used rather than how many times they were used(115,124). Thus, NiTi rotary files submit to reduced flexural fatigue resistance with repeated usage(97). The majority of deformations and fractures appeared to occur after repeated uses in complex anatomically configurations, with almost all NiTi deformations happening after use in molar teeth(124). As a result of the existing signs of deterioration, it was unable to provide a proper recommendation as to a safe number of rotational NiTi file uses because use varies based on the tooth, operator, and root canal morphology, among other factors(124).

2.7.8. Cross-Section Dimensions and Design

It has been established that increasing the diameter and cross-section of a file increases torsional failure resistance but decreases flexural fatigue failure resistance(125). Researchers compared a larger diameter with triangular cross-sections of ProTaper files to a smaller diameter with U-fluted cross-sections of ProFile instruments and found that the ProTaper model had lower and better stresses distribution than the ProFile model, implying that the Protaper model had more stiffness, greater resistance to torsional stress, and could be used in narrow or calcified canals whilst a Profile model exhibited more flexible, better resistance to flexural fatigue and should be used in cases of severely curved canals(126,127). A radial land was also a surface that extended axially between flutes from the central axis. Those landing instruments have a lower cutting efficiency and stay more centered in the canal during use, but it does not appear to affect fracture resistance(127).

2.7.9. Impact of Instrument Size and Taper

Smaller instruments were shown to be more prone to torsional failure than bigger instruments, according to some researchers(126). On the contrary, a major clinical cohort research found that stiffer, larger diameters, and taper files were not necessarily safer, and that more caution was needed to avoid instrument separation. This shows that when these larger and more hard files are used, they are subjected to more stress(128).

2.7.10. Impact of Manufacturing Process

Conventional NiTi endodontic files were machined from a blank NiTi alloy wire during manufacture, as previously stated. The procedure results in an uneven surface with grooves, pits, and many cracks, and the files become brittle(129). These surface faults could serve as a stress concentration point, causing cracks to occur during clinical use. Surface imperfections also have an impact on the material's ultimate strength and the instrument's fatigue resistance. As a result, manufacturers have attempted to improve the mechanical properties of the files during the manufacturing process by modifying the surface of the alloy microstructure(129).

2.7.11. Impact of the Temperature

The investigations were conducted to establish the number of cycles required for endodontic rotary NiTi files directed at room temperature to fracture. In vivo, these files operate at a temperature close to that of the body, which can impact the results. In comparison to room temperature, body temperature was found to have a substantial impact on minimizing cyclic fatigue of NiTi rotary files(130).

2.8. Prevalence and Incidence of File Separation

The occurrence of instrument fracture during root canal preparation is not rare. The incidence of NiTi instrument fracture has been estimated to be between 0.4 and 5% of root canal procedures(131).

In a retrospective study published in 2006 by Iqbal *et al*(115), they investigated the incidence of hand and rotary instrument separation (IS) in the University of Pennsylvania's endodontics graduate program between 2000 and 2004. There were 81 separate instruments among 4,865 endodontic resident cases; 12 were handled stainless steel files and 69 were rotary NiTi files. The incidence of hand and rotary IS were found to be 0.25% and 1.68%, respectively. The rate of rotary IS was seven times higher than the rate of hand IS. When compared to the coronal and middle thirds of the canals, 67 (82.7%) separated in the apical third roughly 6 times more often, 12 (14.8%) in the middle third, and 2 (2.5%) in the coronal third. IS was found in the highest percentages in mandibular (55.5%) and maxillary (33.3%) molar. Furthermore, the odds of separating a file in molars were 2.9 times greater than premolars.

Spili *et al* 2005(132), did another retrospective analysis in which clinical and radiographic follow-up of at least one year was available for assessment of the retained broken instruments in a total of 8460 non-surgically treated cases in two endodontic practices. Despite the fact that the fractured instruments were either a rotary NiTi file, an SS hand file, a paste filler, or a lateral spreader, the data showed that 2.8% of teeth (235/8460) had a retained fractured rotary NiTi file. Thus, the prevalence of a tooth with a retained separated NiTi rotary file increased to 4.4%, and it was indicated that it may be reasonable to recall that the files were created of conventional NiTi at the time of this investigation. Only until 2007 were heat-treated NiTi files available to clinicians. If heat-treated NiTi files were used, the chance of file fracture would be reduced.

Di Fiore PM *et al* 2006(133), conducted a prospective research to investigate the occurrence of NiTi rotary instrument fracture in endodontic clinical practice. For one year, from May 2003 to April 2004, data on rotary instrument fracture during endodontic treatment of patients were collected prospectively by 11 second-year post-graduate endodontics residents using four NiTi rotary instrument systems (ProFile, ProTaper, GTRotary, and K3Endo) according to the manufacturers' recommendations for instrumented 3181 canals in 1403 teeth (354 anterior teeth, 320 premolars, 729 molars) in 1235 patients. The incidence of instrument fracture was calculated based on the number of instruments used. After the fractures occurred, data was collected on the type, size,

taper, and previous use of the broken instruments, as well as the length and location of the fragment within the root canal and the canal's curvature. The overall incidence of instrument fracture was 0.39%, according to the researchers. In terms of fracture incidence, there was no statistically significant difference between instrument systems. The Instrument fractured 1.9% of teeth (26/1403), with anterior teeth accounting for 0.28% (1/354), pre-molar teeth for 1.56% (5/320), and molar teeth accounting for 2.74% (20/729). There were 26 fractured instruments in total, with 23 of them having tapers of 0.06 or more. The majority of the fragments were found in the apical third of the root canal and were 2mm in length.

2.9. Impact of File Separation on the Healing of Endodontic Treatment

When an endodontic file fractured in the canal, it was critical for the clinician to understand the consequences of this error on the endodontic treatment's outcome. According to Grossman (1969), a retained file fragment lowers the success percentage of endodontic therapy(134). In vital pulp extirpation cases and pulpless teeth with no area of rarefaction, the prognosis is favorable when an instrument has been fractured in the root canal (if an area of rarefaction was not present at the time of the accident). When there is a preoperative area of rarefaction, the repair has a less than 50% chance of occurring, according to the study(134).

In a retrospective study, Spili *et al* 2005(132) have aimed to determine the frequency of instrument fracture and its impact on treatment outcomes from an analysis of specialist endodontic practice records involving 8460 cases. A case-control study of treatment outcomes was undertaken on a subgroup of 146 teeth with a retained instrument fragment (plus 146 matched controls) with at least one year of clinical and radiological follow-up. Overall healing rates for patients with a fractured instrument were 91.8% for patients with a fractured instrument and 94.5% for matched controls in the case-control study. Teeth with a preoperative periapical radiolucency had a poorer healing rate in both groups (86.7% versus 92.9%, respectively)(132).

When a fractured instrument fragment is retained within a root canal, the prognosis for endodontic treatment does not change significantly. However, if periapical disease was present at the time of treatment, the prognosis was worsened, but only to the extent that efficient canal disinfection was compromised(135).

2.10. Generation of Rotary NiTi Endodontic Files

In a highly competitive market, manufacturers have introduced many of the new NiTi rotary files with the goal of providing more efficient and safer file systems. Each new generation of files is distinguished from the preceding one by creative file design and a modification in NiTi metallurgy. The advancements are based on changes to the files' cross-section, taper, and metallurgy.

2.10.1. First-Generation Files

In 1992, Dr. John McSpadden designed the first rotary 0.02 taper NiTi instrument. In 1994, Dr. Johnson introduced the Profile Dentsply 0.04 tapered series, which was followed by the ProFile 0.06 tapered series and the orifice shapers. The use of a more conventional NiTi alloy, cross-sectional shapes generated by machining three equally spaced U-shaped grooves, the presence of radial land area, a passive planing action, a constant file taper, and a negative rake angle resulting in a scraping action of dentin rather than cutting action were the main features of these files. LightSpeed Endodontics 1992, Quantec SybronEndo 1996, and GT system Dentsply 1998 were all rotary file lines that came out shortly afterward in this category(38,136).

2.10.2. Second-Generation Files

In 2001, the second generation of NiTi rotary files was released on the market. The lack or limited usage of radial lands, the positive rake angle resulting in active cutting action, and the use of several variable file tapers were the key differences from the first generation. Protaper® (Dentsply Tulsa Dental Specialties®) is the archetype file of this

generation, with a loyal following. K3 SybronEndo, Mtwo VDW, Hero Shaper Micro Mega, I Race, and I Race Plus FKG Dentaire were some notable systems in this generation(38,136).

2.10.3. Third-Generation Files

To improve the microstructure of NiTi alloys, various innovative thermomechanical processing and manufacturing technologies were developed in late 2007. This generation was more concerned with metallurgy than with file geometry. M-Wire® (Dentsply Tulsa Dental Specialties), R-phase (SybronEndo®), and CM Wire® or Controlled-Memory Wire (DS Dental®) are three main designations that emerged during this time. In comparison to the first two generations, these new NiTi alloys have greater superelastic properties. The fact that these files were kept in their martensite phase at room/body temperature explained their increased flexibility and resistance to cycle fatigue. At room/body temperature, the NiTi alloy of the first two generations of files mostly functioned in the austenite phase. NiTi alloys with a bigger proportion of the martensite phase show more flexibility when compared to files with a more austenite phase present. Examples of files of this generation were K3 XF Files-SybronEndo, Profile GTX Series–Dentsply, controlled memory (CM) Files (HyFlex CM)–Coltene, and Vortex Blue (Dentsply Tulsa) are notable files in this group that has been exposed to heat treatments to increase flexibility and safety(38,136).

2.10.4. Fourth-Generation Files

Because of its mode of operation, the fourth generation of files distinguished out from the prior three. Engine-driven NiTi files were employed in a rotating motion until 2011, when the fourth generation files were introduced. By disengaging the tip of the file within the dentin substrate and extending the instrumentation time before file failure, the constant clockwise-counterclockwise motion had the advantage of carefully maintaining the original path of the root canal and inferior incidence of file fracture. These files share some second-generation geometric advancements as well as third-generation metallurgical advancements. WaveOne® (Dentsply Tulsa Dental Specialties®),

Reciproc® (VDW®), and ReDent Nova's self-adjusting file (SAF) are examples of this generation(38,136).

2.10.5. Fifth-Generation Files

This generation is designed with an offset center of rotation. The offset designed files produce a “snake-like” mechanical wave of motion that distributes along the entire length of the NiTi file during rotation, resulting in less engagement of the file with the dentin, as well as reduced screw effect and taper lock of the rotary file, and thus reduced torsional stresses on the file. Dentin debris is removed more effectively, and dentin sludge is less compacted against the root canal wall, according to the manufacturer. Example files of this latest generation. ProTaper Next® (Dentsply Tulsa Dental Specialties®) and TRUShape® (Dentsply Tulsa Dental Specialties®) HyFlex/electrical discharge machining (EDM)-Coltene, Revo-S-Micro-Mega, One Shape Micro-Mega (38,136).

2.11. Design Features of Protaper Next, Hyflex CM, EdgeFile, and XP-endoShaper

Design features, in addition to other factors such as material properties and handling procedures, influenced the instrument's operating technique and the range of objectives that it could solve by its use. The following are some of the instrument's design features:

2.11.1. The Protaper Next Systems

The Protaper Next (PTN; Dentsply Maillefer) rotary system features a lower overall instrument number, a smaller tip, and a taper that is incomparable to Protaper universal, allowing for a more conservative apical preparation. These instruments were also non-landed, with a noncutting tip made of M-wire alloy for increased flexibility and resistance to cyclic fatigue, as well as design features like variable progressive tapers for increased file strength and an off-centered rectangular cross-section that gives the file a snake-like "swaggering" movement as it moves through the root canal. Asymmetric

Rotary (AR) Motion that increases the effectiveness of ProTaper canal shaping by creating more space for debris hauling (or removing). Finally, these instruments' motor settings and sequence numbers are as follows: motor setting as manufactured 300rpm / 2Ncm and sequence set numbers; X1 with a D₀ diameter of 0.17mm and a 0.04 taper, X2 with a D₀ diameter of 0.25mm and a 0.06 taper, X3 with a D₀ diameter of 0.30mm and a 0.07 taper, X4 with a D₀ diameter of 0.40mm and a 0.06 taper, And X5 with a D₀ diameter of 0.50mm and a 0.06 taper(5) (Figure 14).

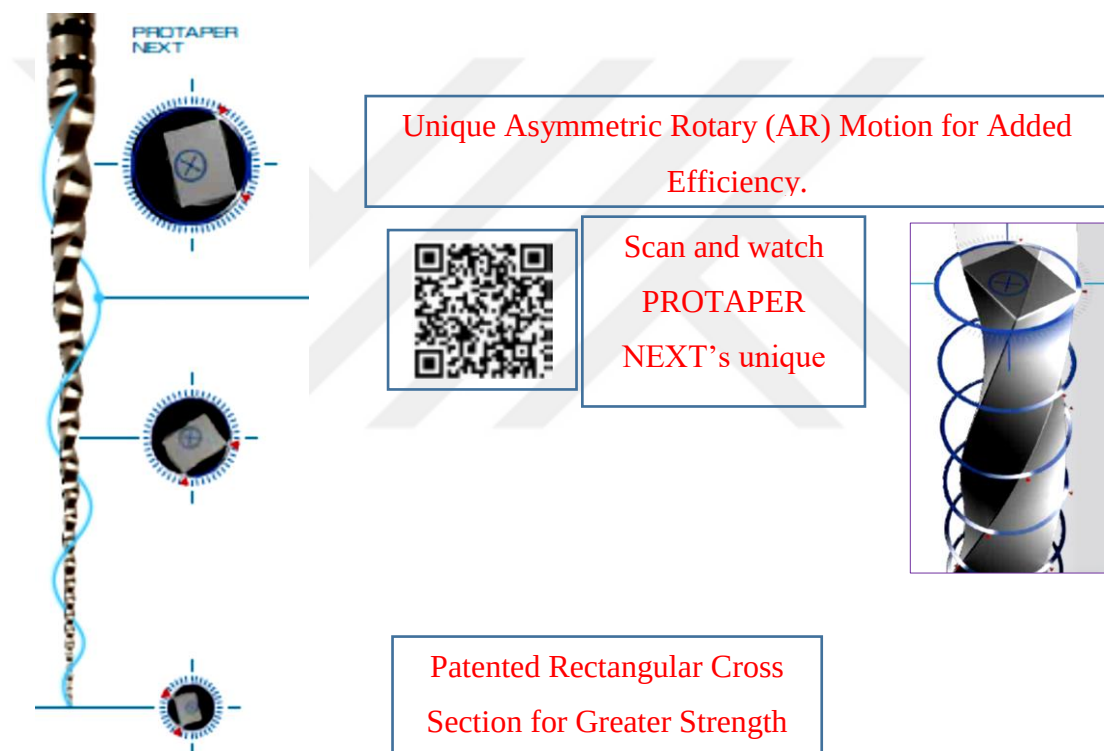


Figure 14. Illustrated Characteristic and Design Features of Protaper Next.

2.11.2. The Hyflex CM Systems

When compared to other NiTi files, HyFlex CM NiTi files with unique Controlled Memory were up to 300 percent more resistant to cycle fatigue, which significantly

reduces the occurrence of file separation. HyFlex Controlled Memory NiTi files have been manufactured utilizing a unique process that controls the material's memory, making the files extremely flexible, but without the shape memory of other NiTi files. This allows the file to precisely track the anatomy of the canal (Superior canal tracking), lowering the risk of ledge formation, transportation, or perforation. These files are multi-use because they regain shape following sterilization (heat treatment), however they should be discarded if they do not return to their original shape. HyFlex CM files can be used with crown-down, step-back, or single-length techniques. Recommended speed and torque setting 500rpm, and 2.5N·cm respectively. The file design features as followed; ISO color-coded on the handle indicated the size of the file, Non-cutting tip, 2 cutting blades, the cross-section was double fluted Hedstrom design and some have triangular, and the printed number indicates the degree of the 3 different tapers, 0.04, 0.06, and 0.08. Besides, these files have accelerated flue designs that provide excellent flexibility, tip strength, and debris transportation(6,137) (Figure 15).

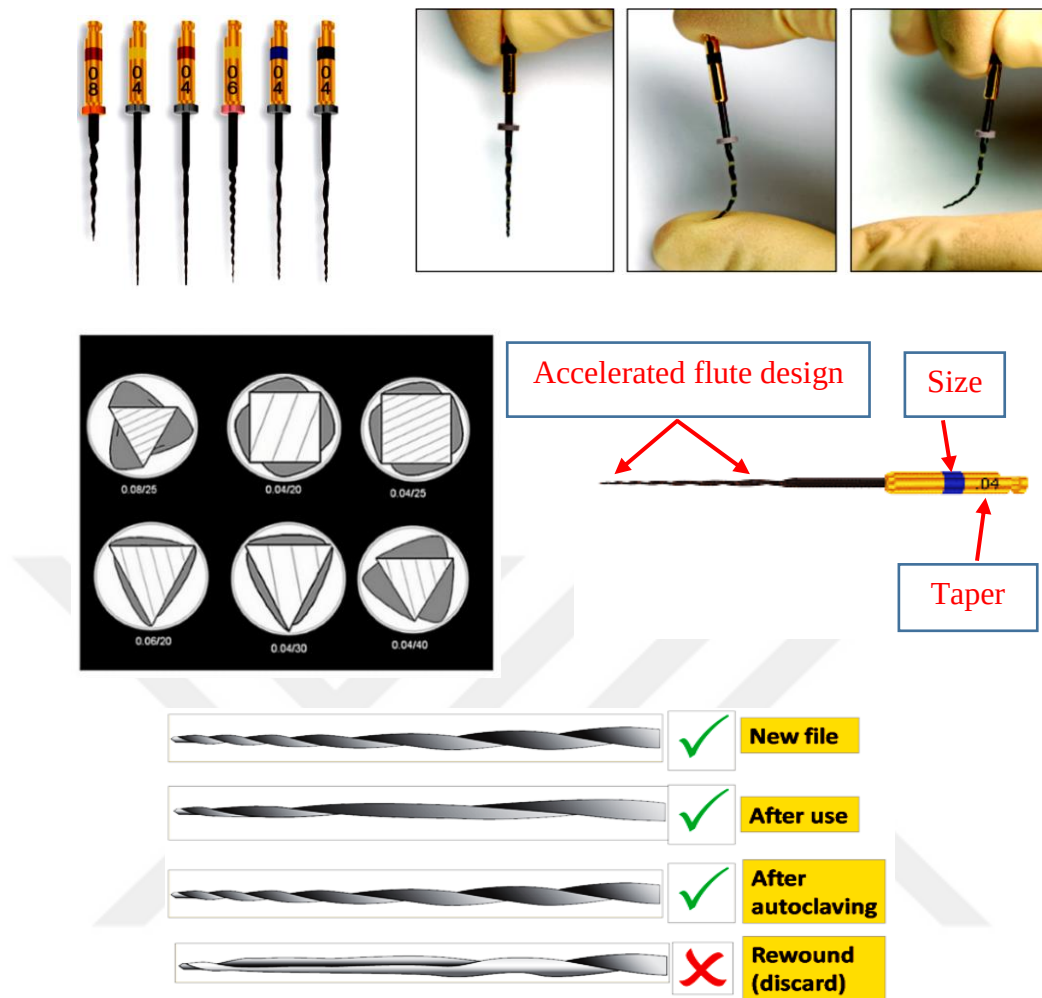


Figure 15. Illustrated Characteristic and Design Features of Hyflex CM files.

2.11.3. The EdgeFile Systems

Based on internal cyclic fatigue testing by manufacture, the instrument is made of an Annealed Heat Treated (AHT) NiTi alloy brand termed Flexible Fire-Wire, which enhances the strength of the loading files by two to eight times. Furthermore, a unique canal contouring method improves the material's properties, making the files extremely flexible and reducing the shape memory and straightening effect that conventional NiTi files have. With the crown down approach, EdgeFile might be used numerous times. These files have the following design features: a non-cutting tip with flutes that comes to

0.25mm of a tip with a parabolic cross-section (annealed heat-treated) for very efficient cutting. Tighter pitch deflects more torsional forces along the length of the file, which means more forces "across" the file, which means increased chances of tearing at the cutting edge. Therefore, heat-treating these files allows the cutting edge to roll instead of tear. Furthermore, the maximum flute diameter is 1mm, thus once the taper reaches 1mm, it becomes a zero taper, preventing strip perforation of the canal. As specified by the manufacturer, the recommended speed and torque are 350-500rpm and 3Ncm, respectively(7,138) (Figure 16).

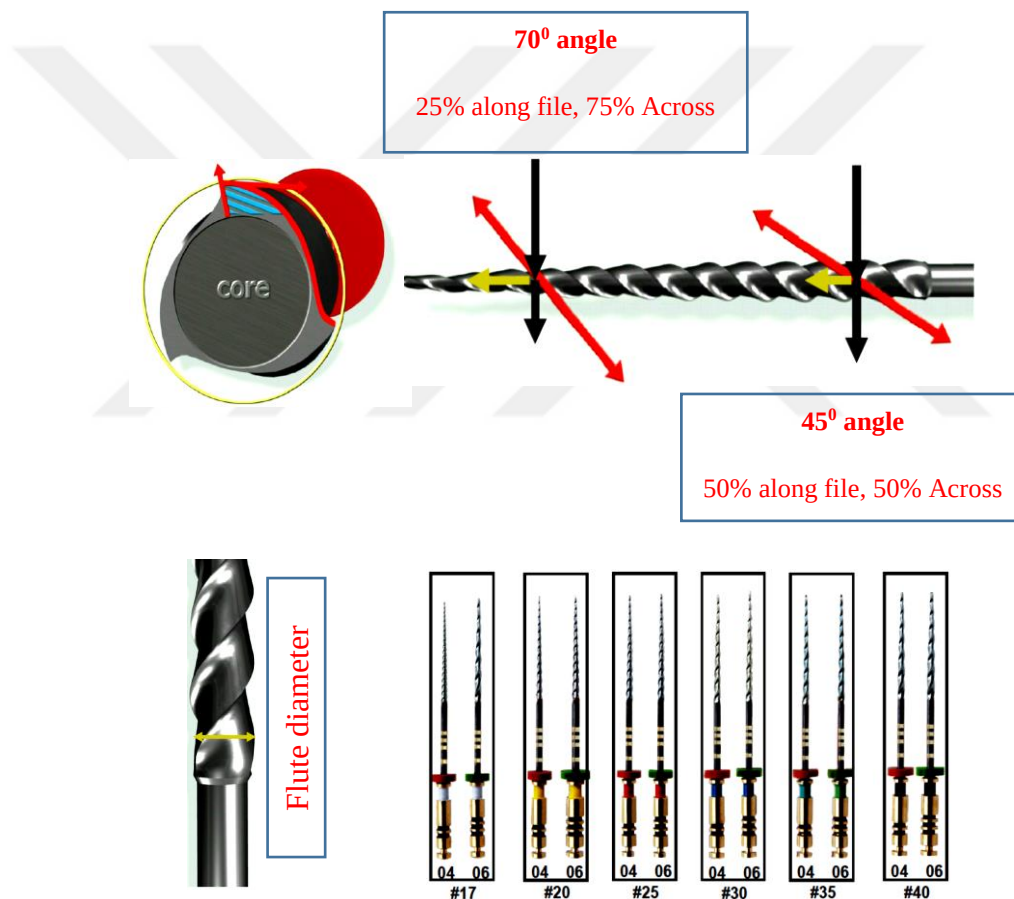


Figure 16. Illustrated Characteristic and Design Features of EdgeFiles.

2.11.4. The XP-endoShaper Systems

Through a constant process of innovation and improvements, FKG introduced XP-endoShaper with the creation of the exclusive MaxWire® alloy for bringing two fundamental properties: superelasticity and shape memory, intending to create a completely new generation of instruments. Unlike other instruments, they can respond to temperature changes and take on a preset form inside the root canal when heated to body temperature. As a result of their unique preconfigured form and high flexibility, these instruments may contract and extend within the canal, allowing them to reach locations that conventional instruments simply can not. Furthermore, its small ISO diameter and narrow taper provide excellent cycle fatigue resistance. These qualities allow this innovative method to treat root canals with extremely complex morphology in a simple and efficient manner while preserving the canal architecture to a surprising degree. These files also contain a booster tip design, which has a unique shape with six sharp edges that follow the canal's path, removing more material with each pass. It aids to start shaping an ISO diameter smaller than the one of the instrument. For example, an ISO 35 instrument with BT-Tip already works at a diameter of 0.15mm. It was a single file technique, and recommended speed and torque as manufactured; 800rpm, 1Ncm respectively(8) (Figure 17).

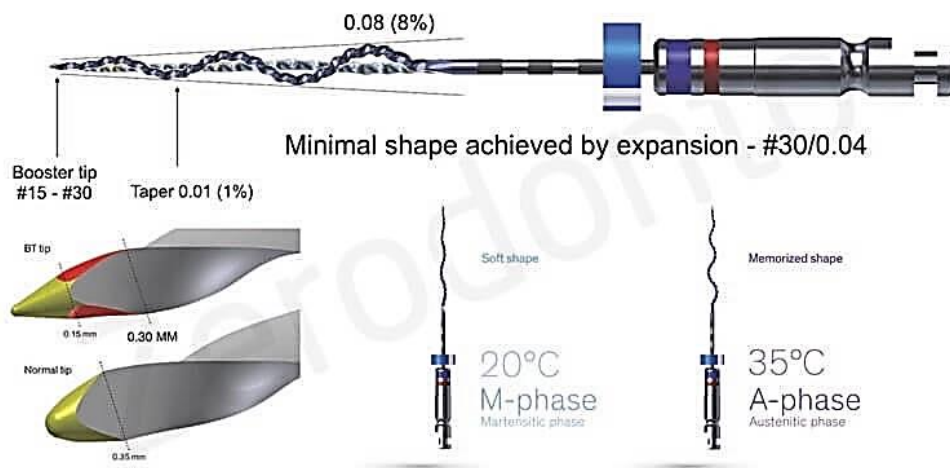


Figure 17. Illustrated Characteristic and Design Features of XP-endoShaper.

2.12. Up to Date Cyclic Fatigue Studied of a Protaper Next, Hyflex CM, EdgeFile, and XP-end Shaper

The tip size and taper of rotary instruments, as well as their design, thermo-mechanical treatment, test temperature, test medium (air or fluid), sterilization, rotation speed (RPM), and trajectory followed by the instruments in the artificial canal, appear to influence their NCF (number of cycles to failure). Many of the research reported in the literature focused on the cyclic fatigue resistance of various rotary NiTi instruments with various alloy systems. The outstanding features of these investigations were analyzed and commented on in order to analyze the results and try to find possible approaches to improve the validity of such investigations (Table 4).

Table 4. Summary of Characteristics of the studies about Cyclic Fatigue.

Author/year	Study type	Type of sample	Sample size (no. of files)	Instrument Used	Kinematic conditions	Comparison Factors	Result (time or NCF)
Plotino G <i>et al</i> , 2014(76)	In vitro	Artificial canal (60° curvature with 5mm radius of curvature)	A total of 60 new files (n=20 from each brand, n= 30 sizes 25/ 0.06, and n= 30 sizes 40/0.04)	Hyflex CM, Vortex, Profile	Static model /room temperature/ at speed 300rpm	Effects of file types on Cyclic fatigue resistance	Hyflex>Vortex and Profile. Vortex=Profile.
Nguyen <i>et al</i> , 2014 (139)	In vitro	Artificial canal (90° curvature with 5mm radius of curvature)	A total of 380 instruments, 20 instruments each of PTN X1–X5, PTU S1–F5, and VB 20/04–50/04	PTN, PTU, Vortex blue(VB)	Static model /room temperature/ Acc. manufactured	Effects of file types on Cyclic fatigue resistance	VB>PTN>PTU
Perez- Higuera <i>et al</i> , 2014 (140)	In vitro	Artificial canal (60° curvature with 3mm radius of curvature)	A total of 420 files (240 PTU, S1, F1, F2, and F3 and 180 PTN, X1, X2, and X3)	PTN, PTU	Static model /room temperature/ Acc. manufactured	Effects of file types on Cyclic fatigue resistance at different levels (at 5, 8mm)	PTU S1 was the highest NCF at 5mm from the tip. PTN >PTU, For PTN X1>X2>X3, For PTU S1>F1>F2>F3.
Elnaghy <i>et al</i> , 2014 (141)		Artificial canal (45° curvature)	A total of 80 new files for each system (	PTN, Hyflex	Static model /room	Effects of file types on	Ranking as TF > PTN > HCM > PT.

	In vitro	with 5mm radius of curvature)	size 25/ 0.06 for PTN X2, HCM, Twisted, and for PTU F1 size 20/0.07.	CM, Twisted, PTU F1	temperature/ Acc. manufactured	Cyclic fatigue resistance	HCM=PTN
Pedulla <i>et al</i> , 2015 (142)	In vitro	Artificial canal (60° curvature with 5mm radius of curvature)	A total of 240 new files. For cyclic fatigue n=70 / size 25/ 0.06 from each system used as 0% (without torsional preloading n=10), 25% n=10 for 20 and n=10 for 40 times of RNTP, and same for 50% and 75%). Remaining numbers of samples for the torsional test.	Mtwo, Hyflex CM, PTN X2	Static model /room temperature/ Acc. manufactured	Cyclic torsional preloading on cyclic fatigue resistance	Hyflex > Mtwo > PTN
I. D. Capar <i>et al</i> , 2015 (143)	In vitro	Artificial canal (60° curvature with 3mm radius of curvature)	A total of 80 new files(n=20 / sizes 25/ 0.06 from each brand)	PTN, Hyflex CM, OneShape, Revo-S	Static model /room temperature/ Acc. manufactured	Effects of file types on Cyclic fatigue resistance	Hyflex highest, Revo-S lowest, and PTN = OneShape
Peng C <i>et al</i> , 2015 (144)	In vitro	Artificial canal (45°, 60°, 90° curvature with 12mm, 9mm, 6mm radius of curvature, respectively)	A total of 60 new files (N=30 for PTN X2 size 25/ 0.06, N=30 for PTU F2 size 25/ 0.08)	PTN, PTU	Static model /room temperature/ at speed 250rpm/2Ncm	Effects of file types on Cyclic fatigue resistance at different curving angles	PTN>PTU at 45° and 60°. PTU>PTN at 90°.
Pirani <i>et al</i> , 2016(77)	In vitro	Artificial canal (70° curvature with 5mm radius of curvature)	A total of 50 new files (30 for Hyflex EDM, n=10 for each size: 25/ 0.08, 40/0.04, 50/0.03. And 20 for Hyflex CM, n=10 for each	Hyflex EDM, Hyflex CM	Static model /room temperature/ Acc. manufactured	Effects of file types on Cyclic fatigue resistance	Hyflex EDM>Hyflex CM

			size: 25/0.04, 40/0.04)				
Uygun <i>et al</i> , 2016(145)	In vitro	Artificial canal (60° curvature with 3mm radius of curvature)	A total of 72 new files (n=24 for PTN X2, n=12 for each level at 5mm and 8mm. N=24 for PTU F2, n=12 for each level at 5mm and 8mm. N=24 for PTG F2, n=12 for each level at 5mm and 8mm).	PTU, PTN, PTG	Static model /room temperature/ Acc. manufactured	Effects of file types on Cyclic fatigue resistance at different levels (at 5, 8mm)	PTG>PTN>PTU at 5 and 8mm from the tip, except at 8 mm PTG=PTN.
Zhao <i>et al</i> , 2016(121)	In vitro	Artificial canal (60° curvature with 3mm radius of curvature)	A total of 400 new with five types of files (n= 80 sizes 30/0.06 for each brand and n=20 in each group)	Hyflex CM, Twisted Files(TF), K3XF, Race, K3	Static model /room temperature/ Acc. manufactured	Effect of autoclave on the Cyclic fatigue resistance	Hyflex CM, TF, and K3XF>Race and K3. Autoclave extended NCF of Hyflex CM and K3XF.
de Vasconcelos <i>et al</i> , 2016 (146)	In vitro	Artificial canal (60° curvature with 3mm radius of curvature)	A total of 160 new with four types of files (40 for PTU F2 size 25/0.08, N=20 for each subgroup at 20°C ± 1°C and 37°C± 1°C. And same for Hyflex CM, TRUShape Vortex Blue sizes 25/0.06 for HCM, TRS, and VB).	PTU F2, Hyflex CM, TRUShape, Vortex Blue	Static model /room and body temperature / Acc. manufactured	Effect of temperature on the Cyclic fatigue resistance	At 20°C, Hyflex >VB> TRUShape>PTU and VB=TRUShape. At 37°C, Hyflex and VB >TRUShape and PTU, also Hyflex=VB. At 37°C, NCF reduced up to 85% for the tested instruments.
Topcuoglu <i>et al</i> , 2016 (147)	In vitro	Artificial canal (Double curvature S-shape, coronal angle of curvature a 50° with 5mm radius	A total of 160 new with four types of files (40 for each brand, PTU F2 size 25/0.08, and size 25/0.06 for PTN	PTU, PTN, OS, HCM	Static model /room temperature / Acc. Manufactured	Impact of curvature on the Cyclic fatigue resistance	At apical curvature, PTN X2 and HCM > OS and PTU F2, also PTN X2 =HCM and OS=PTU F2.

		of curvature and apical angle of curvature a 70° with a radius of 2mm)	X2, Hyflex CM, and OneShape)				At coronal curvature, PTN= HCM=OS=PTU.
KM Elbatouty <i>et al</i> , 2016(148)	In vitro	Two artificial canals with angles 45°, 60°. Each angle with two different radii (2.5 and 5mm).	A total of 160 new with two types of files (n=80/each brand) were used. PTN X3 size 30/0.07, and NRT size 30/0.06. Each brand is divided into two groups based on the angle of curvatures (n=40/each angle). Each group of angles was further subdivided into two groups based on radii of curvatures (n=20/each radius)	PTN X3 and NRT	Static model /room temperature/ Constant speed 250 rpm and torque 5.2 for PTN, 2.8 Ncm for NRT	Impact of angle and radii of curvature on the Cyclic fatigue resistance	NRT > PTN at 5mm radii at both angles, and no significant difference at radii 2.5 mm. NCF reduced once increasing angle of curvature and decreased the radius
Pedulla <i>et al</i> , 2017 (149)	In vitro	Artificial canal (60° curvature with 5mm radius of curvature)	A total of 300 new files from two types (Fifty files from each brand divided into 5 groups, n=10). PTN X1: X2, and Mtwo size 10/0.4, size 15/0.05, size 20/0.06, size 25/0.06).	PTN, Mtwo	Static model /room temperature / Acc. manufactured	Cyclic fatigue resistance at continuous and interrupted rotation (at 1s every 10 or 20s, and 5s every 10 or 20s, respectively)	No difference in terms of interrupted rotation in all instruments. Except, Interrupted rotation reduced NCF of PTN X2 and Mtwo 25/0.06.
Ozyurek T <i>et al</i> , 2017(150)	In vitro	Artificial canal (60° curvature	A total of 60 new files from three types (20 HCM 25/0.06, 20	HCM, EdgeFile,	Static model /room temperature /	Effects of file types on Cyclic	HCM=EdgeFile= Typhoon CM

		with 5mm radius of curvature)	Typhoon CM 25/0.06, and 20 EdgeFile X3 25/0.06).	Typhoon CM	Acc. manufactured	fatigue resistance	
Dosanjh <i>et al</i> , 2017 (130)	In vitro	Artificial canal (60° curvature with 5mm radius of curvature)	A total of 360 new files from three types (120 for EdgeFile size 25/0.04 and subdivided to 4 subgroups at 3°C, 22°C, 37°C, and 60°C, n=30 in each subgroup), same for Vortex Blue and ESX	EF, VB, ESX	Static model /ice water (3° ± 0.5°C), room temperature (22°C ± 0.5°C), body temperature (37°C ± 0.5°C), and hot water (60°C ± 0.5°C) / Acc. manufactured	Effect of the temperature on the Cyclic fatigue resistance	For each temperature, The EF>VB>ESX. VB and ESX showed ↓ NCF as temperatures ↑ from 3°C to 60°C. EF showed ↑ NCF from 3°C to 22°C and ↓ NCF from 22°C to 37°C.
Cai JJ, <i>et al</i> , 2017 (151)	In vitro	Artificial canal (45° curvature with 3mm radius of curvature)	A total of 72 new files from two types (36 for Hyflex CM size 25/0.06 and subdivided to 3 groups n=12 for each group as No immersion, Immersion into NaOCL 5.25% for 10 minutes, and into EDTA 17% for 10 minutes). Same for M3 CM.	HCM, M3 CM	Static model /room temperature / Acc. manufactured	Effect of the irrigation on the Cyclic fatigue resistance	No effect on NCF in both instruments
A. M. Elnaghy <i>et al</i> , 2017 (152)	In vitro	Artificial canal (60° curvature with 5mm radius of curvature)	A total of 320 new files from four types. For cyclic fatigue n=80, twenty from each system with size 25/0.08 for PTU F2 and PTG F2, and size 25/0.06 for PTNX X2 and TRUShape.	PTU, PTN, PTG, and TRS	Static model / room temperature / Acc. manufactured	Effects of file types on Cyclic fatigue resistance	PTG and PTN>TRS and PTU. PTG=PTN. TRS>PTU.

Özyürek T <i>et al</i> , 2017(153)	In vitro	Artificial canal (60° curvature with 5mm radius of curvature)	A total of 240 new files from three types. For cyclic fatigue n=80 from each system PTU F2 size 25/0.08, PTN X2 size 25/0.06, and PTG F2 size 25/0.08. Each system is divided into 4 groups, n=20 of each group according to sterilization protocols.	PTU, PTN, and PTG	Static model / room temperature / Acc. manufactured	Effect of autoclave on the Cyclic fatigue resistance	PTG>PTN>PTU . Autoclave ↑ NCF of PTG and PTN.
Amr Elnaghy <i>et al</i> , 2018 (91)	In vitro	Artificial canal (60° curvature with 3mm radius of curvature)	A total of 150 new files from five types/n=30 each system. Size 30/0.01 for XPS, size30/0.04 for VB, HCM, iRace, and size 30/0.06 for TRS.	XPS, VB, HCM, iRace, and TRS	Static model / body temperature / Acc. manufactured	Effects of file types on Cyclic fatigue resistance	XPS>HCM>VB >TRS>iRace. HCM=VB.
Silva <i>et al</i> , 2018(92)	In vitro	Artificial canal (60° curvature with 5mm radius of curvature)	A total of 40 new files from two types, n=20 /each system. For cyclic fatigue, XPS with size 30/0.01, and TRS with size 30/0.06v (n=10 from each system). Other numbers for another test.	XPS, TRS	Static model / body temperature / Acc. manufactured	Effects of file types on Cyclic fatigue resistance	XPS>TRS
Adiguzel <i>et al</i> , 2018 (154)	In vitro	Artificial canal (60° curvature with 3mm	A total of 80 new files from two types, n=20 /each system. XPS size 30/0.01, HCM size 30/0.04, FlexMaster size	XPS, HCM, FlexMaster , And Race	Static model / body temperature / Acc. manufactured	Effects of file types on Cyclic fatigue resistance	XPS>HCM>FlexMaster>Race

		radius of curvature)	30/0.04, and Race size 30/0.04)				
Keskin <i>et al</i> , 2018 (155)	In vitro	Artificial canal (60° curvature with 5mm radius of curvature)	A total of 54 new files from two types, n=18/each system. XPS size 30/0.01, K3XF size 30/0.04, and PTG F3 size 30/0.09v.	XPS, K3XF, PTG	Static model / body temperature / Acc. Manufactured	Effects of file types on Cyclic fatigue resistance	XPS>PTG and K3XF. PTG=K3XF
Pedulla <i>et al</i> , 2018 (156)	In vitro	Artificial canal (60° curvature with 5mm radius of curvature)	A total of 210 new files from two types, n=105/each system. HCM and TF size 25/0.06. Each system is divided into 7 groups (n=15/ each group) based on the study protocol.	HCM, TF	Static model / 37°C at immersion and room temperature for cyclic fatigue / Acc. Manufactured	Effects of immersion in NaOCl and sterilization on the Cyclic fatigue resistance	No difference at all, except in groups were sterilized 3 times with and without immersion in NaOCl, HCM > TF. Autoclave did not affect NCF except NCF of TF ↓ in these groups. There were not any influence of Immersion in NaOCl on NCF.
Pedullà E <i>et al</i> , 2018 (157)	In vitro	Artificial canal (60° curvature with 5mm radius of curvature)	A total of 120 new files from five types, n=24 /each system. PTN X2, Revo-S SU, Mtwo, TF, and Endwave with size 25/0.06 were used. Each system is divided into two groups (n=12) based on the motion tested: in continuous rotation and reciprocation of OTR motion.	PTN, Revo-S, Mtwo, TF, and EndoWave	Static model / room temperature / At speed 300 rpm.	Effects of motion on the Cyclic fatigue resistance	Mtwo and TF > PTN, Revo-S, and EndoWave at both of the motions. Mtwo=TF, PTN > Revo-S, and EndoWave. Revo-S=EndoWave at both of the motions. Reciprocation of OTR ↑ NCF of all instruments compared with continuous rotation.

Shen <i>et al</i> , 2018 (158)	In vitro	Artificial canal (60° curvature with 5mm radius of curvature)	A total of 360 new files from six types, n=60 /each system. Endosquence, Profile, K3, K3XF, Hyflex CM, Vortex with all of size 25/0.04). Each system divided into 5 groups (n=12/ each group) based on preset of temperature at 0°C, 10°C, 22°C, 37°C, and 60°C.	Endosquence, Profile, K3, K3XF, Hyflex CM, and Vortex	Static model / Differents set of temperature / At speed 300 rpm.	Effects of temperature on the Cyclic fatigue resistance	NCF ↑ from a drop of temperature 60°C to 0°C. At 0°C, NCF OF K3XF was the highest one. At 10°C, K3XF, Vortex, and HCM >Endosquence, Profile, and K3. At 22°C, 37°C, and 60°C, Vortex files were the highest one followed by Hyflex CM. At 0°C and 22°C, no difference in NCF of HCM.
Bueno CRE <i>et al</i> , 2019 (159)	In vitro	Artificial canal (60° curvature with 5mm radius of curvature)	A total of 80 new files from four types, n=20 /each system. Genius size 25/0.04, Genius size 30/0.04, WaveOne Gold Primary size 25/0.07, and EdgeFile X1 size 20/0.06.	Genius, WaveOne Gold Primary, and EdgeFile X1.	Static model/room temperature / At speed 350 rpm with reciprocation motion.	Effects of file types on Cyclic fatigue resistance	EdgeFile X1>Genius and WaveOne Gold Primary. Both of Genius > WaveOne Gold Primary.
A. Bhatt <i>et al</i> , 2019 (160)	In vitro	Artificial canal (60° curvature with 5mm radius of curvature)	A total of 125 new files from five types, n=25 /each system. Hero Shaper, PTN X2, Profile Vortex, HCM, OneShape with all of size 25/0.06.	Hero Shaper, PTN, Profile Vortex, HCM, and OneShape	Static model/room temperature / At speed 400 rpm with torque 2.5 Ncm	Effects of file types on Cyclic fatigue resistance	HCM>OneShape >PTN>Profile> Hero Shaper.
Hacer Akse <i>et</i>			A total of 72 new files from four types, n=36 /each system. Each system is divided into				At immersion in NaOCl, ↓ NCF of XPS whilst no

<i>al</i> , 2019(161)	In vitro	Artificial canal (60° curvature with 5mm radius of curvature)	three groups (n=12) based on a set of immersions, NaOCl 5.25% and RC Prep for 10 minutes at 37°C. XPS with size 30/0.01 and Hyflex EDM size 25/~.	XPS, and Hyflex EDM	Dynamic model/ body temperature / Acc. Manufactured	Effects of immersion solutions on the Cyclic fatigue resistance	effect on Hyflex EDM. At immersion in RC Prep, ↓ NCF of both instruments. Regardless of irrigants, NCF of XPS=Hyflex EDM.
K Olcay <i>et al</i> , 2019 (162)	In vitro	Artificial canal (60° curvature with 5mm radius of curvature)	Totally 45 new, 15/each system. WOG (25/.07), PTN (25/.06), 2Shape (25/.06) files	WOG, PTN, and TS	Static model/ body temperature / Acc. Manufactured	Effect of file types on Cyclic fatigue resistance	WOG>PTN>TS
Paulo Jorge Palma <i>et al</i> , 2019 (163)	In vitro	Artificial canal (45° curvature with 5mm radius of curvature)	90 instruments of three different NiTi rotary file systems (30/each system)s, PTN (size 25, 0.06 taper), HCM (25, 0.06), and EDM (25/~, variable taper), Each system divided into 3 groups/n=10 each group based on the study protocol	PTN, HCM, and EDM	Dynamic model/ body temperature / Acc. Manufactured	The effect of NaOCl immersion on the cyclic fatigue resistance	EDM>HCM>PTN. Immersion in NaOCl decreased the resistance to cyclic fatigue of all tested instruments
Ertuğrul İF, 2019(164)	In vitro	Artificial canal (60° curvature with 5mm radius of curvature)	A total of 90 instruments of three different NiTi rotary file systems (30/each system)s, One Curve (OC), OneShape (OS), and Protaper Next (PTN) X2 with size 25/0.06. Each system divided into 2 groups/n=15	OC, OS, and PTN	Static model/ body temperature / Acc. Manufactured	The effect of NaOCl immersion on the cyclic fatigue resistance	OC>OS>PTN at both solutions. NaOCl solution significantly reduced NCF of PTN, whilst other files no significantly affected

			each group based on the study protocol				
RM Cardoso <i>et al</i> , 2019(165)	In vitro	Artificial canal (90° curvature with 5mm radius of curvature	A total of 72 instruments from three types (n=24/ each brand) were used. XP-endo Shaper (30/0.01), ProDesign Logic (30/0.05), and iRaCe (30/0.04). Each brand was subdivided into two subgroups(n=12) according to temperatures 20°, and 37°.	XPS, PDL, and iRace	Dynamic model/ room and body temperature / Acc. Manufactured	The effect of temperatures on the cyclic fatigue resistance	XPS > PDL > iRace. Body temperature significantly lowers the NCF compared to room temperature
A. M. Elnaghy <i>et al</i> , 2020(166)	In vitro	Artificial canals with double curvature (coronal curve; 60° curvature, 5mm radius and apical curve; 70° curvature and 2mm radius) and single curvature (60° curvature, 5mm radius)	A total of 120 instruments for each system from four types were divided into two groups (n = 60/group) according to the size of the instrument. Then, each group was subdivided into two subgroups (n = 30/group) according to the curvature of the canals (single or double). Size 20/.04 taper and size 25/0.04 of HCM, VB, and RC were used. For TRN instruments, size 20/.04 taper (small) and size	HCM, VB, RC, and TruAnatomy	Static model/ body temperature / Acc. Manufactured	Effects of the angle of curvatures on the Cyclic fatigue resistance	TRN and HCM>VB and RC at both angles. TRN=HCM.

			26/.04 taper (prime) was used				
Abdullah Mahmoud Riyahi, 2020(167)	In vitro	Artificial canal (60° curvature with 5mm radius of curvature)	A total of 45 NiTi files were distributed into 3 different groups (n= 15 per group). PTN X2, TF with size 25/0.06, and TN Prime File with tip size 26/0.04	PTN, TF, and TN	Static model/ room temperature / at 300 rpm	Effects of file types on Cyclic fatigue resistance	TN>TF>PTN
Uslu <i>et al</i> , 2020(168)	In vitro	Artificial canals with double curvature (coronal curve; 60° curvature, 5mm radius and apical curve; 70° curvature and 2mm radius)	A total of 80 NiTi files from four types of (n=20/each type). VDW.ROTATE (size25/0.04), TruNatomy Prime (size26/0.04), HyFlex CM (size25/0.04) and 2Shape TS(size25/0.04)	VDW ROTATE, TruNatomy Prime, HCM, and TS	Static model/ body temperature / Acc. Manufactured	Effects of file types on Cyclic fatigue resistance	VDW ROTATE and HCM>TruNatomy and TS at both curvatures. VDW ROTATE=HCM. TruNatomy=TS.
Mustafa Gündoğar <i>et al</i> , 2020(169)	In vitro	Artificial canal (60° curvature with 5mm radius of curvature)	A total Of 80 NiTi files from four types of (n=20/each type). VDW.ROTATE (size25/0.04), TruNatomy Prime (size26/0.04), HyFlex CM (size25/0.04) and 2Shape TS(size25/0.04)	VDW ROTATE, TruNatomy Prime, HCM, and TS	Static model/ body temperature / Acc. Manufactured	Effects of file types on Cyclic fatigue resistance	VDW.ROTATE > HyFlex CM > 2Shape > TruNatomy
H. S. Topcuoglu <i>et al</i> , 2020(170)	In vitro	Artificial canal (Double curvature S-shape, coronal angle of	A total of 160 new files from four types, n=40 /each system. Each system is divided into two groups based on the preset of	One Curve, Edgefile, HCM, and PTN	Dynamic model/room and body temperature / Acc. Manufactured	Effects of temperature on the Cyclic fatigue resistance	At room temperature, HCM=One Curve=EdgeFile. At body temperature,

		curvature a 60° with 5mm radius of curvature and apical angle of curvature a 70° with a radius of 2mm)	temperature, at room temperature (20° ±1.0°C), and body temperature (35°±1.0°C). One curve, EdgeFile, HCM, PTN X2 with all of size 25/0.06 were used.				OneCurve, and EdgFile>HCM. At both temperatures, PTN was the lowest one. At body temperature ↓ NCF of all instruments.
--	--	--	---	--	--	--	--

2.13. Up To Date Bending Resistance Studies of a Protaper Next, Hyflex CM, EdgeFile, and XP-endoShaper

There were a few published articles that assessed the bending resistance properties of numerous file systems. To this date, according to our knowledge on Pubmed research, there were few published studies in the bending resistance of the Protaper next, Hyflex CM, and EdgeFiles. However, no articles for XP-endo Shaper files have yet been published.

G. Pongione *et al*, 2012(171). The goal of the research was to see if this novel manufacturing approach generates NiTi instruments (Hyflex) that are more flexible and/or resistant to cyclic fatigue than those made using a traditional manufacturing procedure or a thermally treated NiTi alloy (M-wire). Twelve .06 size 25 Hyflex instruments (Coltene, Allstatten, Switzerland), twelve 06.25 Vortex instruments (Dentsply-Tulsa, OK, USA), and twelve 06.25 Endosequence instruments (Brasseler, Savannah, GA, USA) were initially evaluated for stiffness on bending. The stiffness test procedures strictly followed ISO 3630-1, and the bending moment was measured when the instrument attained a 45 degrees bend. The results of the study show the ability of the new CM-wire manufacturing process to yield NiTi rotary instruments more flexible.

Santos *et al*, 2013(172). This study aimed to assess the flexibility and torsional stiffness of a controlled memory (CM) nickel-titanium (NiTi) file and compare its mechanical reactions with those of a superelastic NiTi file with the same geometry using finite element simulation. The geometry of the HyFlex instrument with a tip size of 30 and a 0.06 taper was selected for this study. The bending resistance test was done by clamped 3mm from the tip of the file and the shaft was deflected until 45° of inclination, the bending moment was calculated. They confirmed the CM NiTi files had higher flexibility and potential fatigue resistance.

Elnaghy and Elsaka *et al*, 2014(173). This study aimed to compare the mechanical properties of ProTaper Next files (PTN) with Twisted Files (TF) and RaCe (RC). The cantilever-bending test was used to determine the bending resistance of files. The load was applied by using a stainless steel wire (length of 40cm and diameter of 0.34mm), with one of the termini fixed to the universal testing machine (Model TT-B; Instron Corp, Canton, MA) and the other end fixed 3mm away from the tip. The bending test was performed until the tip of each file underwent an elastic displacement of 45°. The load cell used was 20N, and the crosshead speed was 15mm/min. They concluded, TF displayed more flexibility compared with PTN and RC files.

Lopes HP *et al*, 2016(174). This study aimed to assess the semiquantitative composition, flexibility, and microhardness of endodontic instruments with conventional and CM NiTi alloy, as well as the influence of continuous rotation and reciprocating motion on static fatigue. Hyflex CM 40/0.04 and RaCe 40/0.04 were submitted to the cantilever-bending test. They concluded that Hyflex CM had higher flexibility.

Chad Hansen *et al*, 2016(138). This study aimed to compare the torsion and bending properties of a brand new file system (EdgeFiles by EdgeEndo, Albuquerque, NM). Ten different file systems were evaluated, Size 30 files of .04 taper, EdgeFile X7, EndoSequence (Brasseler), Vortex Blue (Dentsply), K3XF (SybronEndo), HyFlex CM (Coltene/Whaledent, Inc.). To test flexibility/stiffness the bending test was performed, The tip of each file was put into the chuck, but at an angle perpendicular to the rotational axis of the motor. The rotating pin, attached to the opposing chuck controlled by the

motor, was made to slightly touch the file without applying forces. The motor was then activated, rotated 45 degrees, and then stopped. The forces applied to the torque- sensing cell were recorded. They concluded that HyFlex CM had the most flexibility followed by X7, EndoSequence, Vortex Blue, then K3XF.

Goo *et al*, 2017(175). The study aimed to compare the bending stiffness, cyclic fatigue, and torsional fracture resistances of heat-treated and conventional NiTi rotary instruments. V-Taper 2 (VT2; #25/.08), V-Taper 2H (V2H; #25/.06), Hyflex CM (HCM; #25/.06), HyFlex EDM (HDM; #25/variable taper), and ProTaper Next X2 (PTN; #25/variable taper) were tested. The bending stiffness was measured with the customized device and the files (n = 15) were fixed at 3mm from the tip and bent at 45° concerning their long axis. The result of the study showed that CM-wire instruments showed higher flexibility and cyclic fatigue resistance than M- wire and conventional NiTi instruments.

2.14. Up To Date Microhardness Studies of a Protaper Next, Hyflex CM, EdgeFile, and XP-endoShaper

There are few studies about microhardness of Protaper Next and Hyflex CM files in the literature. In addition, no studies have been found in the literature evaluating the microhardness of XP-endoShaper and EdgeFile. However, in order to evaluate the results and find possible methods to enhance the validity of such studies, the outstanding features of these studies were studied and assessed.

Elnaghy and Elsaka *et al*, 2014(173). This study aimed to compare the mechanical properties of ProTaper Next files (PTN) with Twisted Files (TF) and RaCe (RC). Vickers microhardness was measured on the cross-section of instruments with a 300g load and 15second dwell time. They concluded that PTN revealed the highest microhardness value which improved its resistance to wear compared with TF and RC.

Elnaghy and Elsaka *et al*, 2017(152). This study aimed to a comparison of the mechanical properties of TRUShape with several NiTi. TRUShape TRS (size 25/.06v taper), ProTaper Next X2 (PTN X2; size 25/.06 taper), ProTaper Gold (PTG F2; size

25/.08 taper) and ProTaper Universal (PTU F2; size 25/.08 taper) instruments were evaluated. The microhardness for each instrument was measured by cutting a 4mm length from the apical portion using a low-speed diamond saw (Isomet 1000, Buehler Ltd., Lake Bluff, IL, USA). Then, the specimens were polished according to ASTM standard (ASTM E3-11 2007) and mounted. A microhardness tester (FM-7, Future Tech. Corp., Tokyo, Japan) with a diamond indenter was used to make 5 micro indentations for each specimen. The load was 300g and the dwell time was 15s. They concluded, the PTU had significantly higher surface microhardness values compared with other tested brands, and the second one was PTN.

Shen *et al*, 2013(51). This study aimed to analyze the type and location of defects in HyFlex CM instruments after clinical use in a graduate endodontic program and to inspect the impact of clinical use on their metallurgical properties. Vickers hardness was measured with a 200g load near the flutes for new and clinically used axially sectioned instruments. They founded no significant difference in microhardness was detected between new and used instruments (with and without defects).

Lopes HP *et al*, 2016(174). This study aimed to assess the semiquantitative composition, flexibility, and microhardness of endodontic instruments with conventional and CM NiTi alloy, as well as the impact of continuous rotation and reciprocating motion on static fatigue. The Vickers microhardness was made to two instruments of each commercial brand, Hyflex CM 40/0.04 and RaCe 40/0.04 were embedded in epoxy resin and to expose the instrument nucleus it was used sandpaper 200, 300, 400, 600 and 1200. Alumina with particles of 0.5µm was used to polish the samples. The Vickers microhardness was made with 100g during 15s using a microdurometer Bhueler model 1600- 5300. Five penetrations were done in the central area of the work portion of each instrument. They revealed no significant difference was observed in the microhardness tests.

2.15. Study Models for Cyclic Fatigue Testing

To date, there was no specification or international standard to test cyclic fatigue resistance of endodontic rotary instruments. An ideal model would involve the instrumentation of curved canals in natural teeth. However, in such tests, a tooth can only be used once and the shape of the root canal will change during instrumentation, making it impossible to standardize experimental conditions(176). Each research explained parameters that they find to be appropriate for their investigation. This focuses on comparing data from several midpoints, which is impractical or perhaps impossible to do. On the basis of the actual and challenging clinical scenario, the best option should be taken. For these reasons, numerous equipment and methodologies were employed to investigate the in vitro cyclic fatigue fracture resistance of NiTi rotary endodontic instruments. In approximately all of the studies described in the endodontic literature, the rotating instrument was either restricted in a glass or metal tube, in a grooved block-and-rod assembly, or a sloped metal block (176) (Figure 18).

Computer-based Finite Element Analysis (FEA) was used for this purpose but was not measured due to the huge amount of variables that interact with each other and the difficulty to duplicate a realistic root canal and rotating file inside into a practical model. Variations of traditional methods to benchmark experiments have been used in this field(19,20). Primary experiments used a glass or metal tube as a means to generate a “canal”. Although practical, different file designs of different sizes would adjust themselves differently inside the tube and thus have slightly different trajectories within the tube. In 1986, The first research examined the impact of cycle axial motion on instrument failure by fatigue testing endodontic files with and without cyclical axial motion in a lubricated lumen of a curved Pyrex capillary tube until failure(177). Another technique was used grooved block-and-rod(178)or inclined planes(110) have been used for assigning curvature on a file for cyclic fatigue testing. Both of these methods had issues with standardizing file curvatures/radii and holding the file tip in a certain place without slipping sideways, which was likely due to increased friction between the file and the wider surface of contact with the block-rod/inclined plane. Although the majority of the experiments were carried out in static settings, the block-rod/inclined plane methodologies show that dynamic testing may be possible(102). Axial or vertical movement along the file's longitudinal axis was designed to simulate the usage of an

endodontic rotary file in the clinic when shaping the canal. Two- or three-point jigs have been used to regulate the file curvature/radius and minimize friction from the block-rod and inclined plane models to address the problem of friction from the prior approach(179,180). When fitted to these jigs, different files may be adapted to different trajectories, as previously described. One of the advantages of such jigs is that they allow cyclic fatigue testing to be conducted in a liquid environment of the researcher's choice (for example, water, sodium hypochlorite, or ethylenediaminetetraacetic acid)(179,181). Finally, Grande *et al* 2006(111). Have offered a custom-made canal within a stainless steel block that closely fits the size and shape for each of the tested files. Although the creation of the custom-made canals took time, it allowed for the optimum fit of the files within their respective canals while also not being too tight to avoid excessive frictional stress on the files(182,183). This latter method was chosen for our experiment.

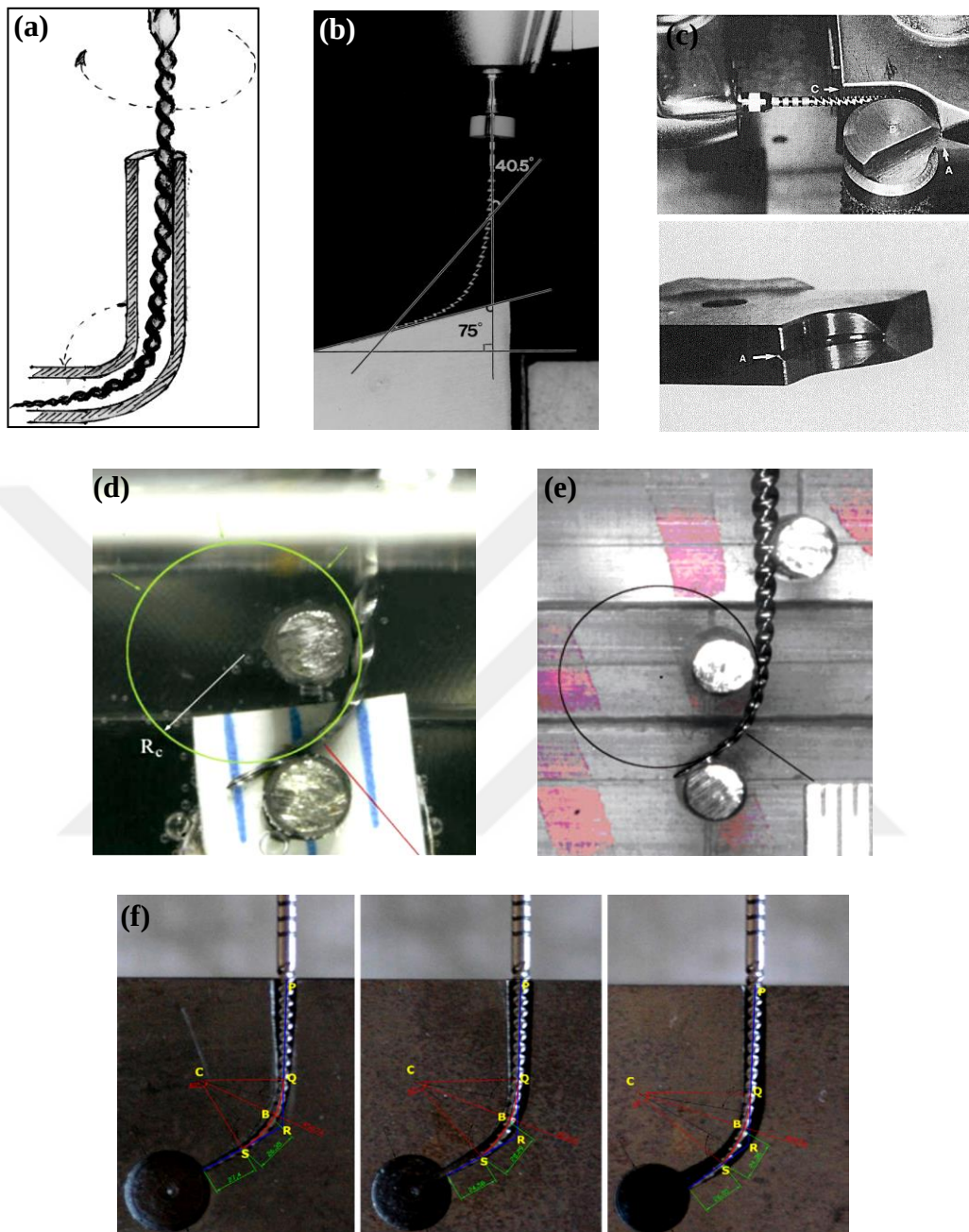


Figure 18. Devices for cyclic fatigue testing: (a) Glass or metal tube, (b) Inclined plane, (c) Grooved block and rod, (d) Two-pin jig, (e) Three-pin jig, and (f) Custom-machined canals.

2.16. Study Models for Bending Resistance Testing

The bending stiffness/ resistance was measured by following the American Dental Association Specification No. 28 and ISO Standard 3630-1 to evaluate their flexibility(22,184). Several modified devices known as cantilever bending tests were used with a similar concept (Figure 19). The files were fixed at 3mm from the tip and then bent 45° along their long axis, with the bending moment was recorded using a load cell or a torsionmeter device(185). Another apparatus was used with the instrument fixed at 3mm from the tip, perpendicular to the axis of the geared motor running clockwise at 2rpm, the bending moment was automatically recorded by the load cell in Ncm, and once the bending lever touched the instrument shaft and set the lever in motion until the instrument was bent by 45° concerning its long axis(186,187). A universal testing machine was used to attach the file between two metal plates on a load-sensing cell and bend the files to a maximum deflection of 4.5mm at a rate of 2mm/minute at room temperature(188), or each file-handle was secured to a chuck and the load was applied in a downward direction at a point 3mm from the tip of each file (1.0 mm/min) by using a universal testing machine(189). Besides, the relative flexibility was determined by a 3-point bending test with a 10-mm span by using customized jig ensured the load cell of the Instron engaged the files at D8 throughout testing(190). The bending resistance test was also carried out by another device, which consisted of instruments that were attached to the mandrel with their cables, with one end of a flexible stainless steel wire that was 50cm long and 0.34mm in diameter fastened to the testing machine's head, and the other end positioned 3mm away from the instrument tip until it displayed a 45° deflection, the maximum load needed to bend recorded(191). Finally, the bending moment was calculated by clamping the file 3 mm from the tip and deflecting the shaft until it reached 45° degrees of inclination(172). The same idea with the new customized device was chosen for our experiment.

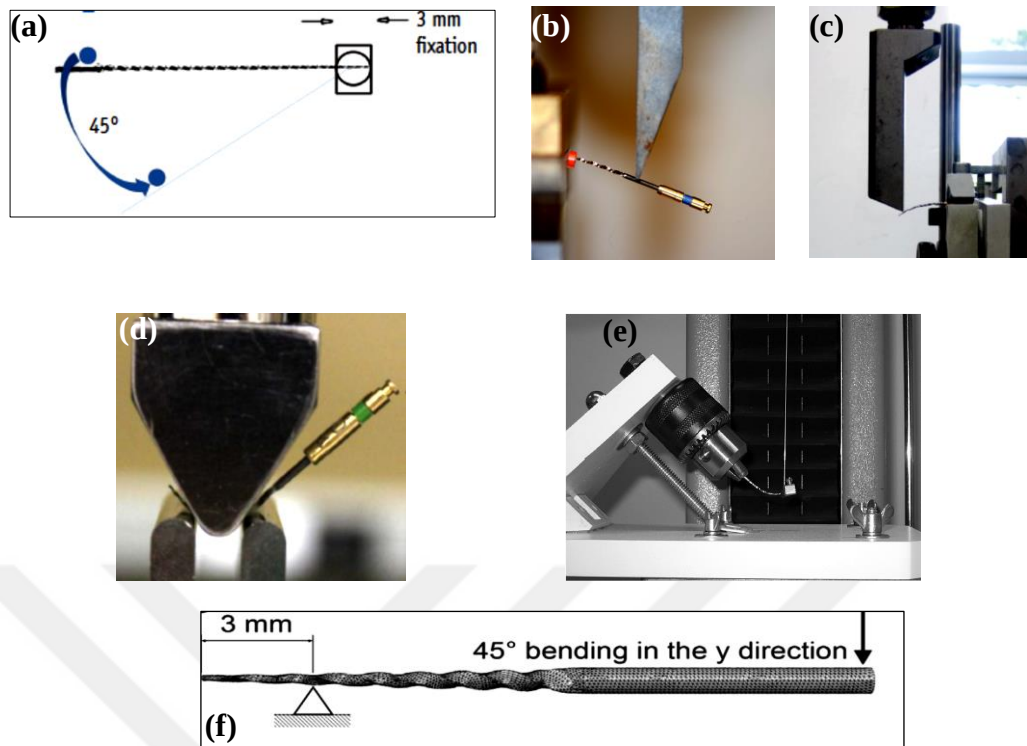


Figure 19. Illustrated Customized Devices for Bending Resistance Testing. (a) Schematic drawing for bending stiffness, (b) Flexibility testing apparatus with 4.5mm deflection, (c) cantilever bending testing, (d) jig used for flexibility testing, (e) The 45° bending test apparatus, and (f) boundary conditions for the bending testing.

2.17. Study Models for Vicker Microhardness Testing

Hardness can be used to predict wear resistance and the ability of NiTi rotary endodontic instruments to abrade tooth structure. The Vicker hardness test was used to learn more about the mechanical characteristics of NiTi instruments. A water-cooled low-speed diamond was used to cut the apical region of each instrument's length of 4 or 6-7mm in order to measure the Vickers microhardness(VHN)(51,88,191). Each specimen was mounted and polished according to ASTM standard E3-11 for the preparation of metallographic specimens (ASTM E3-11 2007)(192). VHN was measured using a digital microhardness tester. A diamond indenter with a 300g load and a dwell time of 15s were used. Five or Ten micro indentations were made for each instrument(51,88,193).

2.18. Aims of the Study

The study was aimed as followed:

1. To evaluate and compare the cyclic fatigue resistance of NiTi endodontic files with different alloys, and within the different angle of the canal curvatures.
2. To evaluate the effect of the sodium hypochlorite immersion on NiTi endodontic files during a cyclic fatigue test.
3. To evaluate and compare the effect of the room and body temperature on the cyclic fatigue resistance of endodontic files.
4. To evaluate the effect of sterilization on the cyclic fatigue resistance of NiTi endodontic files.
5. To evaluate and compare the bending resistance of NiTi endodontic files with different alloys.
6. To evaluate and compare the surface microhardness of NiTi endodontic files with different alloys.

2.19. Hypothesis

Study Null hypotheses tested as followed:

1st hypothesis

Cyclic fatigue resistance was not affected by different types of NiTi alloy.

2nd hypothesis

There was no difference in cyclic fatigue resistance under investigation of angle and curvature locations.

3rd hypothesis

There was no difference between air and moisture conditions (NaOCI immersion) on the cyclic fatigue resistance.

4th hypothesis

There was no difference between room and body temperature on the cyclic fatigue resistance.

5th hypothesis

The use of sterilization was no effect on cyclic fatigue resistance.

6th hypothesis

The bending resistance was not affected by different types of NiTi alloy.

7th hypothesis

The microhardness was not affected by different types of NiTi alloy.

3. MATERIAL AND METHODS:

A total of 480 NiTi instruments were used in this study. 120 files from each brand, Protaper Next- X3 (PTN; Dentsply Sirona Maillefer, Ballaigues, Switzerland) (30/0.07), HyFlex CM (HCM; Coltene Endo/Whaledent, Inc, Cuyahoga Falls, OH, USA) (30/0.04), and EdgeFile –X7 (EFX7, EdgeEndo, USA) (30/0.04), and XP-endoShaper (XPS; FKG Dentaire, La Chaux-de-Fonds, Switzerland) (30/0.01) instruments rotary files instruments with over length 25mm was used as in the (Table 5, Table 6, and Figure 20).

Table 5. Specifications of the NiTi instruments used in this study.

Type of instrument	Sample No	Size	Length(mm)	Speed(rpm)	Torque (NCM)	Manufacture
Protaper Next	120	30	25	300	2	PTN; Dentsply Maillefer, Ballaigues, Switzerland
Hyflex CM	120	30	25	500	2.5	HCM; Coltene Endo / Whaledent, Inc, Cuyahoga Falls, OH, USA
EdgeFile	120	30	25	500	3	EFX7, EdgeEndo, USA
XP-endoShaper	120	30	25	800	1	XPS; FKG Dentaire, La Chaux-de-Fonds, Switzerland

Table 6. Features of the main automated instrumentation systems used in this study.

Instrument/ Manufacturer (Year)	Application/Kinematics	Taper %	Cross- section/Special Features	Manufacturing/ Treatment
Protaper Next (2013)	Shaping/Rotary eccentric	7 (Variable)	Off-centered rectangular	Micro milling, Premanufacture heat treatment: M-wire
Hyflex CM (2011)	Shaping/ Rotary centric	4 (Constant)	Double fluted Hedstrom design with positive rake angle	Micro milling, Post- manufacture heat treatment: CM
EdgeFile (2015)	Shaping/ Rotary centric	4 (Constant)	Parabolic cross- section (annealed heat-treated)	Annealed Heat Treated NiTi alloy brand named Fire-Wire
X- endoShaper (2015)	Shaping/Rotary eccentric	1	Triangular Booster Tip	Micomilling, Shape- setting, Heat-treatment Max-X-Wire

Before subjected to cyclic fatigue and other mechanical testers, all the files were inspected used a dental operating microscope (Carl Zeiss surgical GmbH, 73446 oberkochen, Germany) under 25x magnification for morphological and dimensional analysis and any sign of visible deformations(152). Any file with faults or defects was discarded.

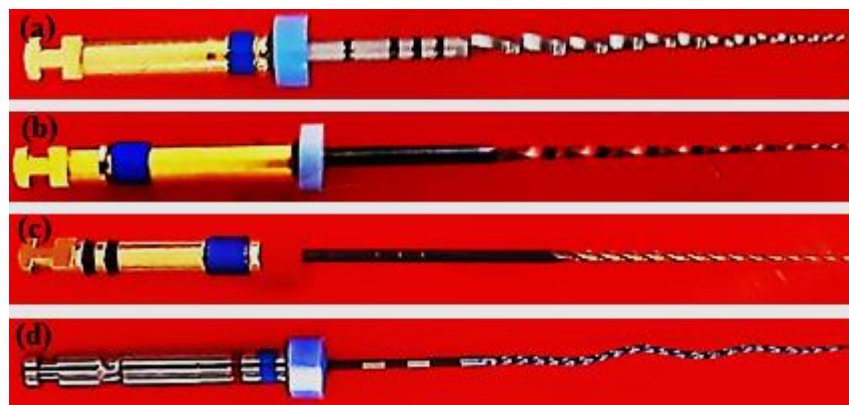


Figure 20. NiTi instruments were used in this study. (a) PTN, (b) Hyflex CM, (C) EdgeFile and (d) XP-endoShaper.

3.1. Methodology Design For the Cyclic fatigue test:

As a result of power analysis using the G*program, when the effect size d : 0.552 and SD: 135 were taken for the cyclic fatigue parameter, the number of samples determined for power: 0.80 and α : 0.05 was determined as a minimum ($n=10$) for each subgroup(121).

Eighty files from each brand, PTN- X3, HyFlex CM, EdgeFile –X7, and XP-endoShaper rotary files instruments with over length 25mm were randomly assigned into four groups ($n=20$) for cyclic fatigue test according to study protocol based on previous methods described by(91,121,156). After that, each group was further divided into two subgroups ($n=10$) and subjected to a fatigue test with two angles of canal curvatures (90^0 and S-shaped) as in (Table 7) respectively based on methods described by Al Sudani *et al*, in 2012(194). The study protocol was accomplished as follows:

Group 1 ($n=20$): In the control group, the instruments were not immersed in NaOCl and were not sterilized and subjected to cyclic fatigue tests in air condition at room temperature.

Group 2 ($n=20$): The instrument was subjected to a cyclic fatigue test within dynamically immersed in 5% NaOCl at the body temperature 37^0 C.

Group 3 ($n=20$): The instruments were subjected to 1 cycle of autoclave sterilization, and then were subjected to a cyclic fatigue test within dynamically immersed in 5% NaOCl at the body temperature 37^0 C.

Group 4 ($n=20$): The instruments were subjected to 5 cycles of autoclave sterilization, and then were subjected to a cyclic fatigue test within dynamically immersed in 5% NaOCl at the body temperature 37^0 C.

For autoclave sterilization, in each cycle was performed sterilization at 134⁰C, with a pressure of 30 psi, for 20 min and then drying for 15 minutes(195).

Table 7. Study protocol design.

Groups	Instruments	$\alpha = 90^0$	$\alpha = S$ shape
Group 1(Control, n=80)	- Protaper next (n=20)	10	10
	- Hyflex CM (n=20)	10	10
-No immersion	- EdgeFile (n=20)	10	10
-No sterilization	- XP endoShaper (n=20)	10	10
-At room temperature			
Group 2 (n=80)	- Protaper next (n=20)	10	10
-5%NaOCl immersion	- Hyflex CM (n=20)	10	10
-No sterilization	- EdgeFile (n=20)	10	10
-At body temperature	- XP endoShaper (n=20)	10	10
Group 3 (n=80)	- Protaper next (n=20)	10	10
-5%NaOCl immersion	- Hyflex CM (n=20)	10	10
-1X sterilization	- EdgeFile (n=20)	10	10
-At body temperature	- XP endoShaper (n=20)	10	10
Group 4 (n=80)	- Protaper next (n=20)	10	10
-5%NaOCl immersion	- Hyflex CM (n=20)	10	10
-5X sterilization	- EdgeFile (n=20)	10	10
-At body temperature	- XP endoShaper (n=20)	10	10

For the cyclic fatigue test, in the control group, the instruments were subjected to cyclic fatigue tests in the air condition at room temperature. In the other groups, the files were subjected to cyclic fatigue tests within the immersion of sodium hypochlorite solution (Saver, Prime Dental, Turkey) at the body temperature by using a Hyger titanium

tube submersible pinpoint aquarium heater with digital thermostat, IC temp controller (Hyger Titanium Aquarium, AU-HG-802-5OW, Class II, China) as in (Figure 21).

A static model for cyclic fatigue testing was conducted in a custom –made device that allowed for a reproducible simulation of instruments confined in a curved canal. All the groups were investigated to cyclic fatigue resistance by used two artificial canals (single curvature and double curvature) based on previous methods described by Al Sudani *et al*, 2012(194). The artificial canal was manufactured with a suitable trajectory that conforms to the parameters of the chosen curvature (Figure 21). The cyclic fatigue metal jig was designed by the 3D Solid works computer program (2015, Turkey) and subjected to computer-aided milling to produce an artificial canal of the following dimensions of 70mm x, 30mm x, 23mm with a trajectory stimulated canal 1.5 mm wide at coronal part, 1.04 mm wide at beginning of the canal curvature and 0.5mm wide at the tip by using a CNC machine (TR-51 Series, Trident Machinery Co., Ltd. Taiwan).

In the artificial canal with a single curve, 90° angle of curvature and a radius of 5mm was used, with the center of the curve located 5mm from the tip of the instrument. The double curve artificial canal (S-shaped), has a coronal curve with 45° angle of curvature and a radius of 5mm, located 9.5mm from the tip of the instrument, and the apical curve with 60° angle of curvature and a Radius of 2mm whose center was placed at 3mm from the tip. All the files were placed in the simulated canal of over length 20mm.

To reduce file friction with artificial canal walls, in the control group, high-flow synthetic lubricating oil (Castrol EDGE OW -40 A3/B4, Turkey) was applied and the free canal surface was covered with tempered glass to prevent the instruments from slipping out and to allow observation of the instruments. And for other groups, the canal space was filled with sodium hypochlorite.

The dental handpiece was constructed on the custom made plastic frame and metal block for precise and reproducible insertion of each instrument into the canal. The

instruments were activated by using an 8:1 reduction handpiece powered by a torque-controlled motor using TF adaptive system endo motor (SybronEndo, 1332 S, Lone Hill Avenue Glendora, CA 91740 USA).

All instruments were rotated until fracture occurred at the speed and torque recommended by the manufacturers. The time to fracture was videos recorded and stopped as soon as a fracture was detected visually and/or audibly using a digital stopwatch 1/100-s with accuracy $\pm 0.01s$ (Casio Stopwatch HS-3, CO., LTD. China) and registered to the nearest integer second(121) (Figure 21).

❖ **Methods of Evaluation of Cyclic Fatigue:**

A. Number of Cycles to Failure (NCF):

The number of cycles to failure (NCF) for each instrument was calculated by multiplying the time (in second) to failure by the number of rotations or cycles per second regardless of the rotational direction (500 rpm for Hyflex CM and EdgeFile, 300 rpm for PTN and 800 rpm for XP-endoShaper according to the manufacturer)(121).

NCF FORMULA:

$$\begin{aligned} \text{NCF} &= \text{RPM set in the endomotor} \\ & \times \text{time taken to fracture} \\ & \text{(number of cycles to failure)} \quad \text{the instruments} \\ \text{NCF} &= \frac{\text{RPM}}{60 \text{ s}} \times \text{time taken to fracture} \\ & \text{the instrument in seconds)} \end{aligned}$$

The length of the fractured fragments was measured in millimeters used a digital caliper with accurate to $\pm 0.01\text{mm}$ (ROHS NORM 2002/95/EC, Qingdao Preco Imp. & Exp. Co., Ltd. China)(91) (Figure 21). Moreover, in the double-curved artificial canal, if the fracture occurred first in the apical curve, the time to fracture and NCF was also registered for the coronal fragment(194). A single operator performed all experimental procedures to eliminate operator bias.

B. Mode of Failure:

The fractured segments of the broken instruments from each group with different brands ($n=1$ from each brand of the file system and group) were collected, ultrasonically cleaned in acetone for 5 min to remove oil (iTronic IR8000EU, Ultrasonic cleaner, China), and then treated with absolute alcohol for 5 min to remove any solution and debris from the surface of the file before the examination to determine the fracture mode(121). Random samples were chosen to be tested under a scanning electron microscope (SEM; EVO40, Carl Zeiss, Germany)(196). Samples were mounted in different situations, one vertically (fracture end facing upward) to obtain top view (fractographic examination) and the other horizontally to achieve lateral view respectively as follows:

1. Top views (cross-sections) with low and high magnifications (500 and 5000X) were taken to evaluate the details and patterns of the fractographic characteristics of the cyclic fatigue fracture surface(196,197) (Table 8).
2. Lateral views with low magnification (250X) were taken to inspect any signs of plastic deformation, disruption of cutting edge and manufacturing grooves, cracks, and quality of surface treatment of the files(197,198) (Table 8).

Table 8. Patterns and signs of cyclic fatigue fracture.

Defect	Definition
Metallic strips	Visible flashes of metal protruding irregularly from the surface
Metallic folds	Rolled over metallic dim appearing along the cutting edge
Disruption of the cutting edges	The loss of the regular continuous shape of the blades
Micro-fractures	A surface defect that appears as surface fissuring and discontinuity, it appears mainly as an accentuation of machine grooving.
Cracks	Break down without complete separation of parts
Fractures	Complete separation of parts
Scrapings	Removed areas from the surface which may be due to excessive frictional force
Pitting	Small, excavated and punched out areas on the surface
Craters	Large excavated areas on the surface
Corrosion	The disintegration of the NiTi alloy due to chemical reaction appears darker in the color than the rest of the surface
Fretting	Observable corrosion with friable surface texture
Debris	Small particles made of materials removed from the canal

3.2. Methodology Design For Bending resistance test:

As a result of power analysis using the G*program, when the effect size d : 2.402 and SD: 24 were taken for the microhardness parameter, the minimum number of samples determined for power: 0.80 and α : 0.05 was determined minimum ($n=12$) for each group(152). The bending resistance of the 20 instruments from each brand (PTN- X3, HyFlex CM, EdgeFile –X7, and XP-endoShaper) was selected based on the previous methods(152,172,199) and investigated by using a cantilever-bending test, as described previously(55,200). The test was performed with a new customized device by clamped the tip of each instrument at 3mm (according to ISO 3630-1 specification) into the Chuck apparatus designed at the base of an Instron universal testing machine (Instron, model 3345, USA) and fastened by used a self-cure acrylic (Imicrylic, dental material, Konya, Turkey. After that, bent the tip of endodontic files 45^0 concerning their long axis by loading force applied directly on the shaft of each instrument. Using an orthodontic stainless steel straight wire fixed on the base of Instron aperture at 45^0 relative to the machine base so that every instrument underwent an elastic displacement of 45^0 with the level parallel to the plane of orthodontic wire. The load cell used was 100N, and the crosshead speed was 15mm/min. The moment of bending at an angular deflection of 45^0 was recorded (Figure 22).

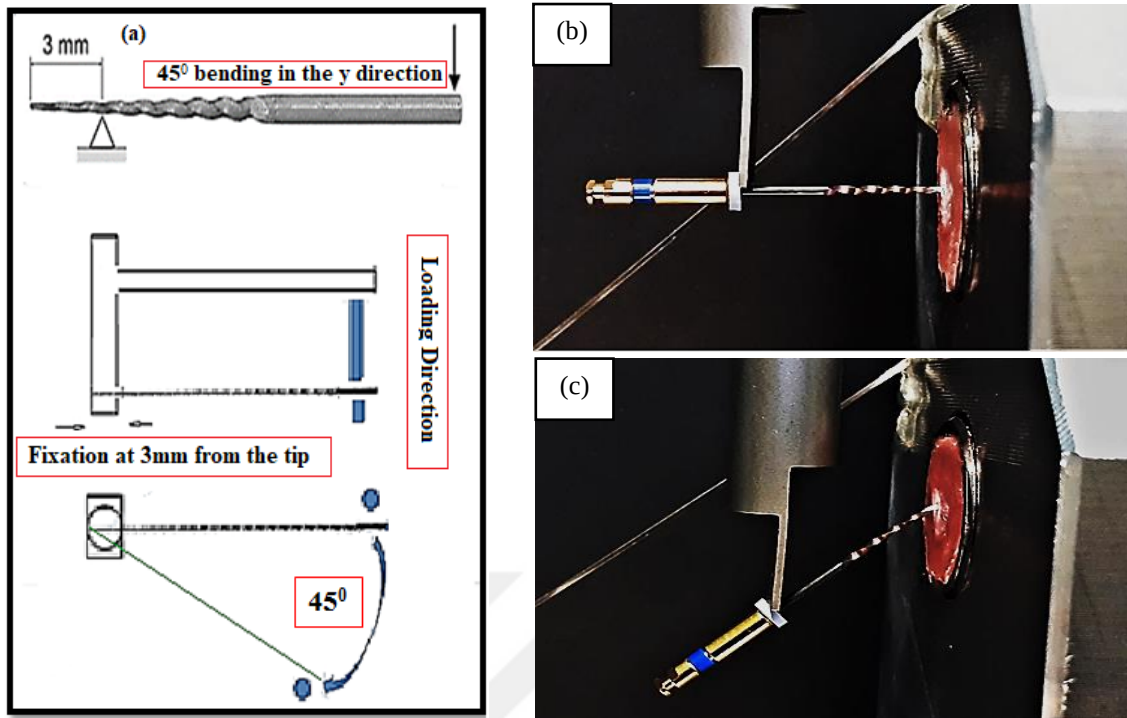


Figure 22. (a). A schematic drawing diagram of a bending resistance test device, (b). Experimental setup showing experimental file fastened in the self-cure acrylic at 3mm from the tip and on the other side of the file showing loading force onto the shaft of instruments using Instron universal testing machine, and (c) Experimental file bent 45° at the tip.

3. 3. Methodology Design For Vickers microhardness test:

As a result of power analysis using the G*program, when the effect size d : 1.386 and SD: 19 were taken for the microhardness parameter, the minimum number of samples determined for power: 0.80 and α : 0.05 was determined as a minimum ($n=12$) for each group(152). Twenty instruments from each brand (PTN- X3, HyFlex CM, EdgeFile –X7, and XP-endoShaper) were selected for the Vickers microhardness test, based on the previous method(51,88,152,173). The apical portion of 6-7mm in the length of each instrument was cut with a water-cooled low-speed diamond saw (Isomet 1000, Buehler Ltd., Lake Bluff, IL, USA) and mounted within self-cure acrylic (Imicrylic, Dental Material, Konya, Turkey), after that, grinding and polished according to ASTM standard E3-11 for the preparation of metallographic specimens (ASTM E3-11 2011) (192) as follows:

The grinding procedures were done in two stages (planar or rough and fine stages), in the planar or rough grinding of instruments was done with used grit P80 and P220 for all brands except XP-endoShaper, and then all of the samples subjected to fine grinding by used fine abrasive papers with grit P1200 onto the grinder/polisher machine (Phoenix Beta, Wirtz Buehler, USA). After all the grinding procedures, all of the specimens were cleaned by the use of ultrasonic cleaner in a distilled water (iTronic IR8000EU, Ultrasonic cleaner, China) and followed by polished all of the samples by the use of loose abrasive synthetic diamond paste embedded in an appropriately lubricated supporting surface. VHN was measured using a digital microhardness tester (MicroMet microhardness tester, Buehler Ltd, Lake Bluff, IL, Illinois USA). A diamond indenter with 300g load and a dwell time of 15s were used(88,173). Five micro indentations were made for each instrument (Figure 23).

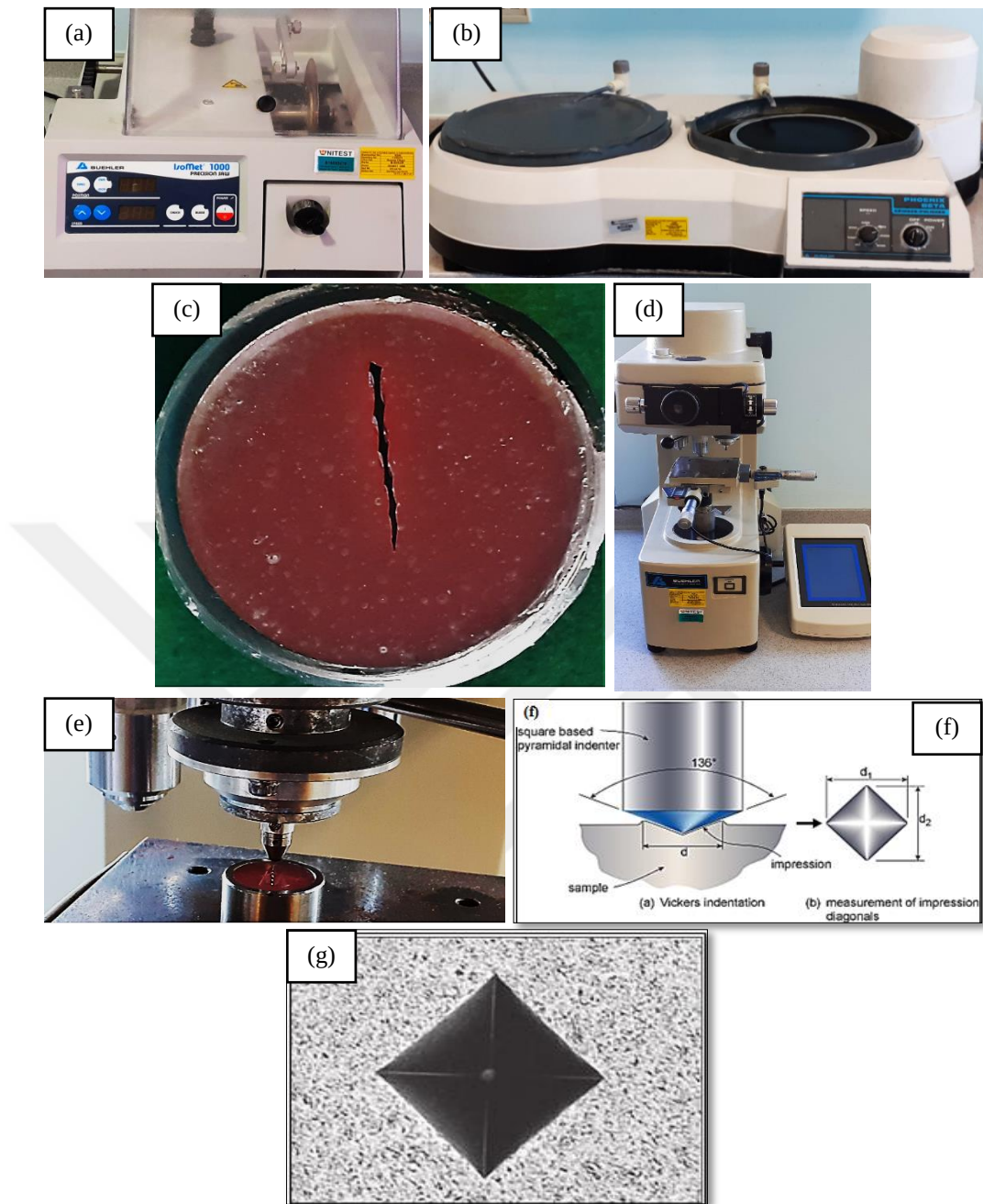


Figure 23. Experimental setup showing, (a) low-speed diamond saw, (b) grinder/polisher machine, (c) Experimental grinding fragment file embedded in the self-cure acrylic, (d) digital microhardness tester, (e) A diamond indenter onto an experimental file, (f) A schematic drawing diagram of a microhardness test device, and (g) Example of a well-formed Vickers indentation from the google.

3. 4. Statistical Analysis:

When evaluating the finding obtained in this study, The numerical data were tested for normality by checking the distribution of data with the Shapiro Wilks test. All the data revealed normal (parametric)distribution. Parametric data were descriptive statistics as mean, standard deviation (SD), and 95% Confidence Interval (95% CI) for the mean values. A three-way Analysis of Variance (ANOVA) test was conducted to determine the effects of file types, medium condition groups, and the angle/curvature locations on both NCF and the separated part's length. When the overall F test indicated a significant difference, Bonferroni's post hoc test was performed to identify comparison significance. A one-way Analysis of Variance (ANOVA) test and Games-Howell post hoc analysis was conducted to determine the effects of a file type on both microhardness and bending resistance. The statistical significance level was established at $p < 0.05$. Statistical analysis was performed with SPSS software (IBM Corporation, NY, USA) version 25 for Windows.

4. RESULTS:

4.1. Results of Cyclic Fatigue Test:

4.1.1. Effect of File Types, Medium Condition Groups, and Angle of Canal Curvatures on NCF:

The descriptive statistics for NCF values based on medium condition groups, file types, and angle of canal curvatures are shown in the tables and figure (Table 9, Table 10 and Figure 24).

Table 9. Descriptive statistics (Mean $\pm$ SD, Min/Max, 95% CI) of the NCF values based on medium condition groups, file types, and angle of canal curvatures.

Medium Condition Groups	File Types	The angle of Canal Curvatures	Mean	Standard Deviation	Minimum	Maximum	95% CI for Mean	
							Lower	Upper
Group 1	Protaper Next	Single Curve	207.8	26.7	182.5	267.5	188.7	226.9
		Double Curve	65.0	20.8	41.4	114.3	50.1	79.8
	Hyflex CM	Single Curve	744.6	145.5	552.8	948.0	640.5	848.7
		Double Curve	272.1	65.2	185.8	402.5	225.5	318.7
	EdgeFile	Single Curve	2913.1	337.2	2393.5	3381.3	2671.9	3154.3
		Double Curve	776.6	56.4	686.9	899.0	736.3	816.9
	XP endoShaper	Single Curve	1652.6	261.9	1300.5	2173.2	1465.2	1839.9
		Double Curve	689.1	90.7	533.1	776.4	624.3	754.0
Group 2	Protaper Next	Single Curve	165.8	26.0	107.6	191.6	147.1	184.4
		Double Curve	50.3	7.2	36.0	60.6	45.2	55.5
	Hyflex CM	Single Curve	690.8	84.0	577.8	815.2	630.7	750.8
		Double Curve	176.1	67.6	86.1	290.5	127.8	224.5
	EdgeFile	Single Curve	2320.8	259.9	1840.0	2610.0	2134.9	2506.7
		Double Curve	329.9	58.9	204.7	406.4	287.7	372.0
	XP endoShaper	Single Curve	1118.0	197.7	827.2	1399.9	976.7	1259.4
		Double Curve	602.6	120.1	447.2	816.4	516.7	688.4
Group 3	Protaper Next	Single Curve	191.9	15.9	173.4	222.5	180.5	203.3
		Double Curve	54.0	7.2	43.5	65.6	48.8	59.1
	Hyflex CM	Single Curve	679.4	86.7	535.4	796.2	617.4	741.4
		Double Curve	175.6	39.0	124.2	241.5	147.7	203.5
	EdgeFile	Single Curve	2421.4	411.3	1929.7	2993.4	2127.1	2715.6

	XP endoShaper	Double Curve	458.4	67.2	364.6	587.7	410.3	506.5
		Single Curve	1063.5	201.9	842.8	1382.8	919.1	1207.9
Group 4	Protaper Next	Double Curve	515.7	106.1	348.0	641.5	439.8	591.6
		Single Curve	216.6	35.8	181.4	271.7	191.0	242.2
	Hyflex CM	Double Curve	84.4	17.4	60.6	106.5	72.0	96.9
		Single Curve	807.0	119.7	676.9	976.2	721.4	892.6
	EdgeFile	Double Curve	205.1	50.2	132.5	278.8	169.2	241.0
		Single Curve	2834.7	287.8	2390.3	3316.3	2628.8	3040.6
	XP endoShaper	Double Curve	464.3	67.7	372.3	607.5	415.9	512.8
		Single Curve	1066.7	210.1	853.7	1397.2	916.4	1217.0
	XP endoShaper	Double Curve	517.4	114.3	385.1	734.7	435.6	599.1
		Single Curve	1066.7	210.1	853.7	1397.2	916.4	1217.0

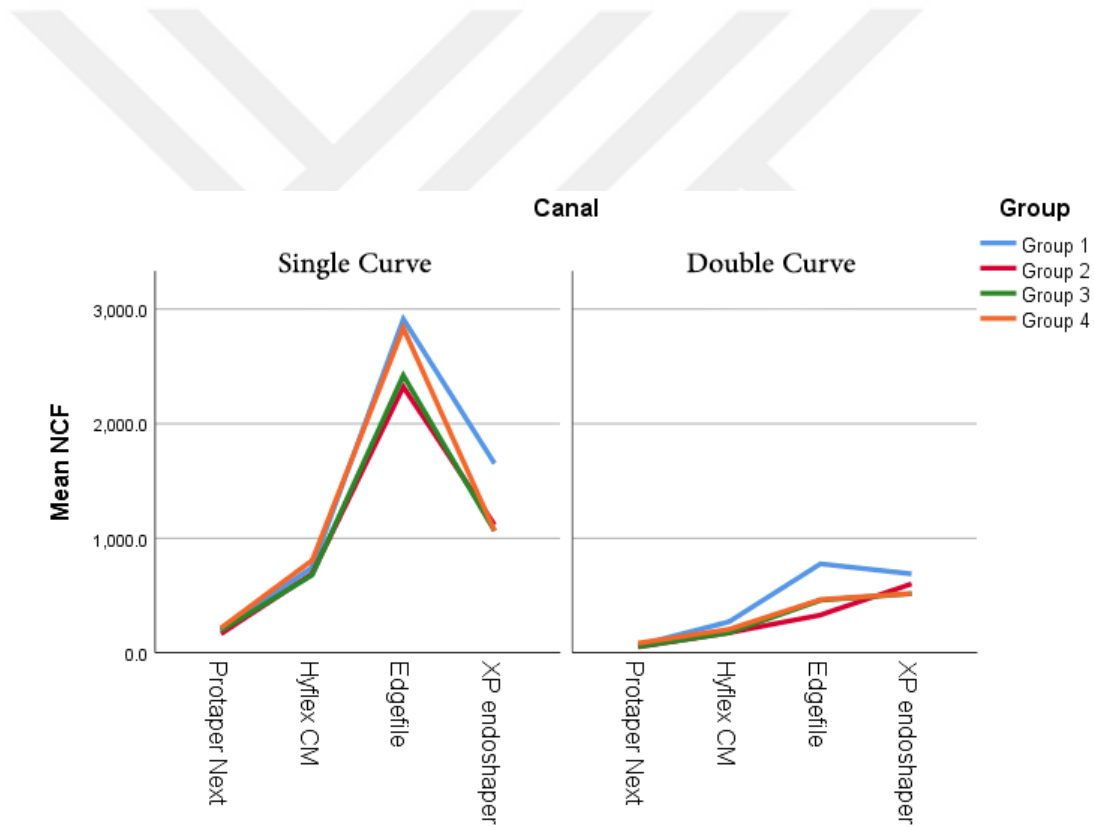


Figure 24. The line graph showed descriptive NCF values based on medium condition groups, file types, and angle of canal curvatures.

All data were normally distributed as assessed by the Shapiro-Wilk test ($p > 0.05$) (Table 10).

Table 10. Shapiro-Wilk test to determine the normality of distribution of the data (The NCF values based on medium condition groups, file types, angle of canal curvatures).

Medium Condition Groups	File Types	Single Curve			Double Curve		
		Statistic	df	Sig.	Statistic	df	Sig.
Group 1	Protaper Next	0.856	10	0.068	0.864	10	0.086
	Hyflex CM	0.925	10	0.402	0.950	10	0.666
	EdgeFile	0.947	10	0.628	0.930	10	0.444
	XP endoShaper	0.938	10	0.529	0.843	10	0.052
Group 2	Protaper Next	0.855	10	0.066	0.940	10	0.558
	Hyflex CM	0.924	10	0.394	0.952	10	0.697
	EdgeFile	0.925	10	0.401	0.934	10	0.489
	XP endoShaper	0.953	10	0.703	0.926	10	0.413
Group 3	Protaper Next	0.929	10	0.440	0.930	10	0.446
	Hyflex CM	0.947	10	0.628	0.957	10	0.756
	EdgeFile	0.887	10	0.158	0.950	10	0.670
	XP endoShaper	0.879	10	0.126	0.911	10	0.285
Group 4	Protaper Next	0.850	10	0.058	0.902	10	0.229
	Hyflex CM	0.879	10	0.129	0.949	10	0.660
	Edgefile	0.965	10	0.841	0.903	10	0.237
	XP endoShaper	0.866	10	0.091	0.925	10	0.401

A. Three-way Interaction:

A three-way ANOVA test was conducted to determine the effects of medium condition groups, file types, and angle of canal curvatures on NCF values. There was a statistically significant three-way interaction between medium condition groups, file types, and angle of canal curvatures, $p < 0.0005$ (Table 11).

Table 11. Three-way ANOVA test to determine the effects of medium condition groups, file types, and angle of canal curvatures on NCF values.

Source	Type III Sum of Squares	Mean Square	F	p
Group * File * Canal	885906	98434	4.171	0.000
Error	6796906	23600		

B. Simple Two-way Interactions:

Medium condition groups and file types: There was a statistically significant simple two-way interaction between medium condition groups and file types in both single curve ($p < 0.0005$) and double canal curves ($p = 0.001$) (Table 12).

Table 12. Simple two-way interaction between medium condition groups and file types on NCF values.

Canals	Sum of Squares	Mean Square	F	Sig.
Single Curve	2730655	303406	12.856	.000
Double Curve	683818	75980	3.219	.001

File types and angle of canal curvatures: There was a statistically significant simple two-way interaction between file types and angle of canal curvatures in all the four medium condition groups ($p < 0.0005$) (Table 13).

Table 13. Simple two-way interaction between file types and angle of canal curvatures on NCF values.

Groups	Sum of Squares	Mean Square	F	Sig.
Group 1	11428263	3809421	161.414	.000
Group 2	10241451	3413817	144.651	.000
Group 3	9708269	3236090	137.12	.000
Group 4	14813324	4937775	209.224	.000

Medium condition groups and angle of canal curvatures: There was a statistically significant simple two-way interaction between medium condition groups and angle of canal curvatures with both EdgeFile and XP-endoShaper files ($p < 0.0005$). However, no statistically significant simple two-way interaction was found between medium condition groups and angle of canal curvatures with both Protaper Next ($p = 0.993$) and Hyflex CM ($p = 0.583$) files (Table 14).

Table 14. Simple two-way interaction between medium condition groups and angle of canal curvatures on NCF values.

Types of File	Sum of Squares	Mean Square	F	Sig.
Protaper Next	2134	711	0.030	.993
Hyflex CM	46099	15366	0.651	.583
EdgeFile	520975	173658	7.358	.000
XP -endoShaper	683837	227946	9.659	.000

C. Simple main effect of file types:

There was a statistically significant simple main effect of the file types in all angles of canal curvatures and medium condition groups ($p < 0.0005$) (Table 15).

Table 15. Simple main effect of file types (Mean $\pm$ SD) of NCF values based on medium condition groups and angle of canal curvatures.

Medium Condition Groups	The Angle of Canal Curvatures	Protaper Next	Hyflex CM	EdgeFile	XP endoShaper	p
Group 1	Single Curve	207.8 (26.7)	744.6 (145.5)	2913.1 (337.2)	1652.6 (261.9)	0.000
	Double Curve	65 (20.8)	272.1 (65.2)	776.6 (56.4)	689.1 (90.7)	0.000
Group 2	Single Curve	165.8 (26)	690.8 (84)	2320.8 (259.9)	1118 (197.7)	0.000
	Double Curve	50.3 (7.2)	176.1 (67.6)	329.9 (58.9)	602.6 (120.1)	0.000
Group 3	Single Curve	191.9 (15.9)	679.4 (86.7)	2421.4 (411.3)	1063.5 (201.9)	0.000
	Double Curve	54 (7.2)	175.6 (39)	458.4 (67.2)	515.7 (106.1)	0.000
Group 4	Single Curve	216.6 (35.8)	807 (119.7)	2834.7 (287.8)	1066.7 (210.1)	0.000
	Double Curve	84.4 (17.4)	205.1 (50.2)	464.3 (67.7)	517.4 (114.3)	0.000

For group 1:

At single canal curvatures, NCF values increased from Protaper Next (207.8 ± 26.7) to Hyflex (744.6 ± 145.5) to XP-endoShaper (1652.6 ± 261.9) to EdgeFile (2913.1 ± 337.2) (Table 15). A statistically significant difference was found between every two files, $p < 0.05$ (Table 16).

At Double canal curvatures, NCF values increased from Protaper Next (65 ± 20.8) to Hyflex (272.1 ± 65.2) to XP-endoShaper (689.1 ± 90.7) to EdgeFile (776.6 ± 56.4) (Table 15). No statistically significant difference was found between EdgeFile and XP-endoShaper ($p = 1.000$). However, there was a statistically significant difference between the other two files, $p < 0.05$ (Table 16).

For group 2:

At single canal curvatures, NCF values increased from Protaper Next (165.8 ± 26) to Hyflex (690.8 ± 84) to XP-endoShaper (1118 ± 197.7) to EdgeFile (2320.8 ± 259.9) (Table 15). A statistically significant difference was found between every two files, $p < 0.05$ (Table 16).

At Double canal curvatures, NCF values increased from Protaper Next (50.3 ± 7.2) to Hyflex (176.1 ± 67.6) to EdgeFile (329.9 ± 58.9) to XP-endoShaper (602.6 ± 120.1) (Table 15). No statistically significant difference was found between Hyflex and both Protaper Next ($p = 0.408$) and EdgeFile ($p = 0.156$). However, there was a statistically significant difference between the other two files, $p < 0.05$ (Table 16).

For group 3:

At single canal curvatures, NCF values increased from Protaper Next (191.9 ± 15.9) to Hyflex (679.4 ± 86.7) to XP-endoShaper (1063.5 ± 201.9) to EdgeFile (2421.4

± 411.3) (Table 15). A statistically significant difference was found between every two files, $p < 0.05$ (Table 16).

At Double canal curvatures, NCF values increased from Protaper Next (54 ± 7.2) to Hyflex (175.6 ± 39) to EdgeFile (458.4 ± 67.2) to XP-endoShaper (515.7 ± 106.1) (Table 15). No statistically significant difference was found between both Protaper Next and Hyflex ($p = 0.466$) and EdgeFile and XP-endoShaper ($p = 1.000$). However, there was a statistically significant difference between the other two files, $p < 0.05$ (Table 16).

For group 4:

At single canal curvatures, NCF values increased from Protaper Next (216.6 ± 35.8) to Hyflex (807 ± 119.7) to XP-endoShaper (1066.7 ± 210.1) to EdgeFile (2834.7 ± 287.8) (Table 15). A statistically significant difference was found between every two files, $p < 0.05$ (Table 16).

At Double canal curvatures, NCF values increased from Protaper Next (84.4 ± 17.4) to Hyflex (205.1 ± 50.2) to EdgeFile (464.3 ± 67.7) to XP-endoShaper (517.4 ± 114.3) (Table 15). No statistically significant difference was found between both Protaper Next and Hyflex ($p = 0.481$), and EdgeFile and XP-endoShaper ($p = 1.000$). However, there was a statistically significant difference between the other two files, $p < 0.05$ (Table 16).

Table 16. Pairwise comparisons of NCF values between file types-based on medium condition groups and angle of canal curvatures.

				Mean Difference	p	95% CI for Difference	
						Lower	Upper
Group 1	Single Curve	Protaper Next	Hyflex CM	-536.8	0.000	-719.3	-354.3
			EdgeFile	-2705.3	0.000	-2887.8	-2522.8
			XP endoShaper	-1444.8	0.000	-1627.3	-1262.2
		Hyflex CM	EdgeFile	-2168.5	0.000	-2351.0	-1986.0
			XP endoShaper	-908.0	0.000	-1090.5	-725.4
	Double Curve	EdgeFile	XP endoShaper	1260.5	0.000	1078.0	1443.0
			Hyflex CM	-207.1	0.003	-389.6	-24.6
			EdgeFile	-711.6	0.000	-894.1	-529.1
		Protaper Next	XP endoShaper	-624.2	0.000	-806.7	-441.7
			EdgeFile	-504.5	0.000	-687.0	-322.0
			Hyflex CM	-417.1	0.000	-599.6	-234.5
			XP endoShaper	87.5	1.000	-95.1	270.0
Group 2	Single Curve	Protaper Next	Hyflex CM	-525.0	0.000	-707.5	-342.5
			EdgeFile	-2155.0	0.000	-2337.6	-1972.5
			XP endoShaper	-952.3	0.000	-1134.8	-769.8
		Hyflex CM	EdgeFile	-1630.0	0.000	-1812.6	-1447.5
			XP endoShaper	-427.3	0.000	-609.8	-244.8
	Double Curve	EdgeFile	XP endoShaper	1202.8	0.000	1020.2	1385.3
			Hyflex CM	-125.8	0.408	-308.3	56.7
			EdgeFile	-279.6	0.000	-462.1	-97.1
		Protaper Next	XP endoShaper	-552.2	0.000	-734.8	-369.7
			EdgeFile	-153.7	0.156	-336.3	28.8
			Hyflex CM	-426.4	0.000	-608.9	-243.9
			XP endoShaper	-272.7	0.001	-455.2	-90.2
Group 3	Single Curve	Protaper Next	Hyflex CM	-487.5	0.000	-670.0	-305.0
			EdgeFile	-2229.5	0.000	-2412.0	-2047.0
			XP endoShaper	-871.6	0.000	-1054.1	-689.1
		Hyflex CM	EdgeFile	-1742.0	0.000	-1924.5	-1559.5
			XP endoShaper	-384.1	0.000	-566.6	-201.6
	Double Curve	EdgeFile	XP endoShaper	1357.9	0.000	1175.4	1540.4
			Hyflex CM	-121.7	0.466	-304.2	60.8
			EdgeFile	-404.4	0.000	-587.0	-221.9
		Protaper Next	XP endoShaper	-461.7	0.000	-644.3	-279.2
			EdgeFile	-282.8	0.000	-465.3	-100.2
			Hyflex CM	-340.1	0.000	-522.6	-157.5
			XP endoShaper	-57.3	1.000	-239.8	125.2
Group 4	Single Curve	Protaper Next	Hyflex CM	-590.4	0.000	-772.9	-407.9
			EdgeFile	-2618.1	0.000	-2800.6	-2435.6
			XP endoShaper	-850.0	0.000	-1032.6	-667.5
		Hyflex CM	EdgeFile	-2027.7	0.000	-2210.2	-1845.2
			XP endoShaper	-259.7	0.001	-442.2	-77.1
	Double Curve	EdgeFile	XP endoShaper	1768.1	0.000	1585.5	1950.6
			Hyflex CM	-120.7	0.481	-303.2	61.8
			EdgeFile	-379.9	0.000	-562.4	-197.4
		Protaper Next	XP endoShaper	-432.9	0.000	-615.5	-250.4
			EdgeFile	-259.2	0.001	-441.8	-76.7
			Hyflex CM	-312.3	0.000	-494.8	-129.8
			XP endoShaper	-53.0	1.000	-235.6	129.5

D. Simple main effect of medium condition groups:

There was a statistically significant simple main effect of medium condition groups in single curve canals with EdgeFile and XP-endoShaper, double curve with EdgeFile groups ($p < 0.0005$), and double curve with XP-endoShaper ($p = 0.005$) (Table 17).

Table 17. Simple main effect of medium condition groups (Mean $\pm$ SD) of NCF values based on the file types and angle of canal curvatures.

The Angle of Canal Curvatures	File Types	Group 1	Group 2	Group 3	Group 4	p
Single Curve	Protaper Next	207.8 (26.7)	165.8 (26)	191.9 (15.9)	216.6 (35.8)	.889
	Hyflex CM	744.6 (145.5)	690.8 (84)	679.4 (86.7)	807 (119.7)	.229
	EdgeFile	2913.1 (337.2)	2320.8 (259.9)	2421.4 (411.3)	2834.7 (287.8)	.000
	XP endoShaper	1652.6 (261.9)	1118 (197.7)	1063.5 (201.9)	1066.7 (210.1)	.000
Double Curve	Protaper Next	65 (20.8)	50.3 (7.2)	54 (7.2)	84.4 (17.4)	.960
	Hyflex CM	272.1 (65.2)	176.1 (67.6)	175.6 (39)	205.1 (50.2)	.456
	EdgeFile	776.6 (56.4)	329.9 (58.9)	458.4 (67.2)	464.3 (67.7)	.000
	XP endoShaper	689.1 (90.7)	602.6 (120.1)	515.7 (106.1)	517.4 (114.3)	.005

For EdgeFile:

At the single canal curve, NCF values increased from group 2 (2320.8 ± 259.9) to group 3 (2421.4 ± 411.3) to group 4 (2834.7 ± 287.8) to group 1 (2913.1 ± 337.2) (Table 17). NCF in group 1 was higher than group 2 by 592.3 ($p = 0.002$) and group 3 by 491.7 ($p = 0.005$) with a statistically significant difference, also group 4 was higher than group 2 by 513.9 ($p = 0.004$) with a statistically significant difference. However, no statistically significant difference was found between the other two groups, $p > 0.05$ (Table 18).

At the double canal curve, NCF values increased from group 2 (329.9 ± 58.9) to group 3 (458.4 ± 67.2) to group 4 (464.3 ± 67.7) to group 1 (776.6 ± 56.4) (Table 17). No

statistically significant difference was found between groups 3 and 4 ($p = 1.000$). However, there was a statistically significant difference between the other two groups, $p < 0.05$ (Table 18).

For XP-endoShaper:

At single canal curve, NCF values increased from group 3 (1063.5 ± 201.9) to group 4 (1066.7 ± 210.1) to group 2 (1118 ± 197.7) to group 1 (1652.6 ± 261.9) (Table 17). No statistically significant difference was found between groups 2 and groups 3 and 4 and between groups 3 and 4 ($p = 1.000$). However, there was a statistically significant difference between the other two groups, $p < 0.05$ (Table 18).

At the double canal curve, NCF values increased from group 3 (515.7 ± 106.1) to group 4 (517.4 ± 114.3) to group 2 (602.6 ± 120.1) to group 1 (689.1 ± 90.7) (Table 17). No statistically significant difference was found between group 1 and group 2, between group 2 and groups 3 and 4, and between groups 3 and 4 ($p = 1.000$). However, there was a statistically significant difference between the other two groups, $p < 0.05$ (Table 18).

Table 18. Pairwise comparisons of NCF values between medium condition groups based on the file types and angle of canal curvatures.

				Mean Difference	p	95% CL for Difference	
						Lower	Upper
Single Curve	EdgeFile	Group 1	Group 2	592.3	0.002	181.4	1003.2
			Group 3	491.7	0.005	80.8	902.6
			Group 4	78.4	1.000	-332.6	489.3
		Group 2	Group 3	-100.6	1.000	-511.5	310.4
			Group 4	-513.9	0.004	-924.8	-103.0
		Group 3	Group 4	-413.4	0.055	-824.3	-2.4
	XP endoShaper	Group 1	Group 2	534.5	0.000	260.6	808.5
			Group 3	589.1	0.000	315.1	863.0
			Group 4	585.9	0.000	311.9	859.9
		Group 2	Group 3	54.6	1.000	-219.4	328.5
			Group 4	51.4	1.000	-222.6	325.3
		Group 3	Group 4	-3.2	1.000	-277.1	270.8
Double Curve	EdgeFile	Group 1	Group 2	446.7	0.000	368.3	525.1
			Group 3	318.2	0.000	239.8	396.6

		Group 2	Group 4	312.3	0.000	233.9	390.6
			Group 3	-128.5	0.000	-206.9	-50.1
		Group 3	Group 4	-134.4	0.000	-212.8	-56.1
			Group 4	-5.9	1.000	-84.3	72.4
	XP endoShaper	Group 1	Group 2	86.5	1.000	- 335.2	497.9
			Group 3	173.4	0.002	94.6	251.8
			Group 4	171.7	0.002	91.9	249.6
		Group 2	Group 3	86.9	1.000	-335.9	498.6
			Group 4	84.9	1.000	-329.8	492.5
		Group 3	Group 4	- 1.7	1.000	-254.3	249.7

E. Simple main effect of angle of canal curvatures:

No statistically significant difference was found between single and double canal curves with Protaper Next file in all four medium condition groups ($p > 0.05$) (Table 19).

For Group 1:

With Hyflex file, NCF in single curve canals (744.6 ± 145.5) was statistically significantly higher than double curve (272.1 ± 65.2) with a mean difference of 472.5 ($p < 0.0005$), and with EdgeFile, NCF in single curve canals (2913.1 ± 337.2) was statistically significantly higher than double curve (776.6 ± 56.4) with a mean difference of 2136.5 ($p < 0.0005$), and finally with XP-endoShaper file, NCF in single curve canals (1652.6 ± 261.9) was statistically significantly higher than double curve (689.1 ± 90.7) with a mean difference of 963.4 ($p < 0.0005$) (Table 19).

For Group 2:

With Hyflex file, NCF in single curve canals (690.8 ± 84) was statistically significantly higher than double curve (176.1 ± 67.6) with a mean difference of 514.6 ($p < 0.0005$), and with EdgeFile, NCF in single curve canals (2320.8 ± 259.9) was statistically significantly higher than double curve (329.9 ± 58.9) with a mean difference

of 1990.9 ($p < 0.0005$), and finally with XP-endoShaper file, NCF in single curve canals (1118 ± 197.7) was statistically significantly higher than double curve (602.6 ± 120.1) with a mean difference of 515.5 ($p < 0.0005$) (Table 19).

For Group 3:

With Hyflex file, NCF in single curve canals (679.4 ± 86.7) was statistically significantly higher than double curve (175.6 ± 39) with a mean difference of 503.8 ($p < 0.0005$), and with EdgeFile, NCF in single curve canals (2421.4 ± 411.3) was statistically significantly higher than double curve (458.4 ± 67.2) with a mean difference of 1963 ($p < 0.0005$), and finally with XP-endoShaper file, NCF in single curve canals (1063.5 ± 201.9) was statistically significantly higher than double curve (515.7 ± 106.1) with a mean difference of 547.8 ($p < 0.0005$) (Table 19).

For Group 4:

With Hyflex file, NCF in single curve canals (807 ± 119.7) was statistically significantly higher than double curve (205.1 ± 50.2) with a mean difference of 601.9 ($p < 0.0005$), and with EdgeFile, NCF in single curve canals (2834.7 ± 287.8) was statistically significantly higher than double curve (464.3 ± 67.7) with a mean difference of 2370.4 ($p < 0.0005$), and finally with XP-endoShaper file, NCF in single curve canals (1066.7 ± 210.1) was statistically significantly higher than double curve (517.4 ± 114.3) with a mean difference of 549.3 ($p < 0.0005$) (Table 19).

Table 19. Simple simple main effect of angle of canal curvatures on NCF values based on the file types and medium condition groups.

Medium condition groups	File Types	Single Curve mean (sd.)	Double Curve mean (sd.)	Mean Difference	p	95% CI for Difference	
						Lower	Upper
Group 1	Protaper Next	207.8 (26.7)	65 (20.8)	142.8	0.055	7.6	278.1
	Hyflex CM	744.6 (145.5)	272.1 (65.2)	472.5	0.000	337.3	607.7
	EdgeFile	2913.1 (337.2)	776.6 (56.4)	2136.5	0.000	2001.3	2271.7
	XP endoShaper	1652.6 (261.9)	689.1 (90.7)	963.4	0.000	828.2	1098.6
Group 2	Protaper Next	165.8 (26)	50.3 (7.2)	115.4	0.094	-19.8	250.7
	Hyflex CM	690.8 (84)	176.1 (67.6)	514.6	0.000	379.4	649.8
	EdgeFile	2320.8 (259.9)	329.9 (58.9)	1990.9	0.000	1855.7	2126.1
	XP endoShaper	1118 (197.7)	602.6 (120.1)	515.5	0.000	380.3	650.7
Group 3	Protaper Next	191.9 (15.9)	54 (7.2)	137.9	0.057	2.7	273.2
	Hyflex CM	679.4 (86.7)	175.6 (39)	503.8	0.000	368.5	639.0
	EdgeFile	2421.4 (411.3)	458.4 (67.2)	1963.0	0.000	1827.8	2098.2
	XP endoShaper	1063.5 (201.9)	515.7 (106.1)	547.8	0.000	412.6	683.0
Group 4	Protaper Next	216.6 (35.8)	84.4 (17.4)	132.2	0.059	-3.0	267.4
	Hyflex CM	807 (119.7)	205.1 (50.2)	601.9	0.000	466.7	737.2
	EdgeFile	2834.7 (287.8)	464.3 (67.7)	2370.4	0.000	2235.2	2505.6
	XP endoShaper	1066.7 (210.1)	517.4 (114.3)	549.3	0.000	414.1	684.5

4.1.2. The Effects of File Types, Medium Condition Groups, and Curvature Locations on NCF:

The descriptive statistics for NCF values depending on medium condition groups, file types, and curvature locations are shown in the tables and graphs (Table 20, Table 21 and Figure 25).

Table 20. Descriptive statistics (Mean $\pm$ SD, Min/Max, 95% CI) of the NCF values based on medium condition groups, file types, and curvature locations.

Medium Condition Groups	File Types	Curvature Locations	Mean	Standard Deviation	Minimum	Maximum	95% CI for Mean	
							Lower	Upper
Group 1	Protaper Next	Apical	65.0	20.8	41.4	114.3	50.1	79.8
		Coronal	183.1	31.4	153.8	258.4	160.6	205.5
	Hyflex CM	Apical	272.1	65.2	185.8	402.5	225.5	318.7
		Coronal	626.2	126.2	480.6	876.7	535.9	716.5
	EdgeFile	Apical	776.6	56.4	686.9	899.0	736.3	816.9
		Coronal	1680.3	250.2	1162.5	2057.3	1501.4	1859.3
	XP endoShaper	Apical	689.1	90.7	533.1	776.4	624.3	754.0
		Coronal	1479.1	233.7	985.1	1863.3	1312.0	1646.3
Group 2	Protaper Next	Apical	50.3	7.2	36.0	60.6	45.2	55.5
		Coronal	169.1	24.5	140.6	225.1	151.5	186.6
	Hyflex CM	Apical	176.1	67.6	86.1	290.5	127.8	224.5
		Coronal	515.0	79.8	442.4	657.5	457.9	572.1
	EdgeFile	Apical	329.9	58.9	204.7	406.4	287.7	372.0
		Coronal	1677.8	171.2	1402.8	1935.2	1555.4	1800.3
	XP endoShaper	Apical	602.6	120.1	447.2	816.4	516.7	688.4
		Coronal	840.2	144.2	653.3	1135.1	737.0	943.4
Group 3	Protaper Next	Apical	54.0	7.2	43.5	65.6	48.8	59.1
		Coronal	170.6	25.5	125.5	216.0	152.3	188.8
	Hyflex CM	Apical	175.6	39.0	124.2	241.5	147.7	203.5
		Coronal	698.3	121.9	535.0	920.8	611.1	785.4
	EdgeFile	Apical	458.4	67.2	364.6	587.7	410.3	506.5
		Coronal	3456.6	550.0	2757.4	4333.6	3063.2	3850.1
	XP endoShaper	Apical	515.7	106.1	348.0	641.5	439.8	591.6
		Coronal	843.6	56.7	748.0	936.0	803.0	884.1
Group 4	Protaper Next	Apical	84.4	17.4	60.6	106.5	72.0	96.9
		Coronal	234.1	47.8	181.3	341.0	199.9	268.3
	Hyflex CM	Apical	205.1	50.2	132.5	278.8	169.2	241.0

		Coronal	921.2	176.6	743.3	1257.6	794.8	1047.5
		Apical	464.3	67.7	372.3	607.5	415.9	512.8
	EdgeFile	Coronal	4170.9	838.5	3035.0	5585.0	3571.0	4770.7
		Apical	517.4	114.3	385.1	734.7	435.6	599.1
		Coronal	898.6	71.3	790.7	1042.7	847.6	949.7

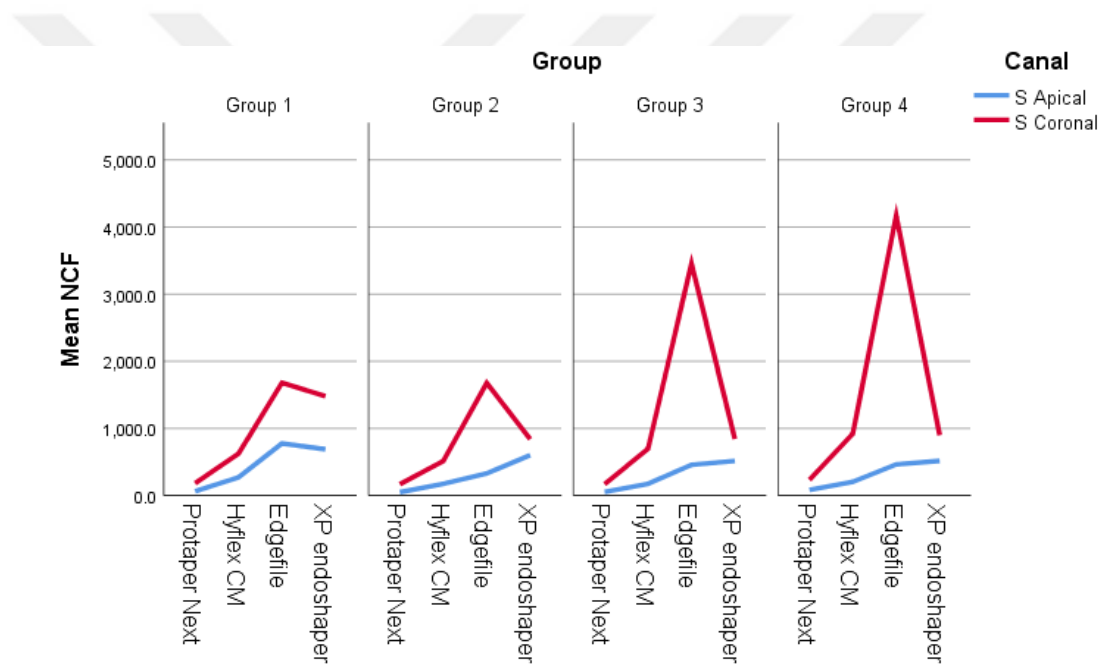


Figure 25. The line graph showed descriptive statistics of NCF values based on medium condition groups, file types, and curvature locations

All data were normally distributed as assessed by the Shapiro-Wilk test ($p > 0.05$) (Table 21).

Table 21. Shapiro-Wilk test to determine the normality of distribution of the data (The NCF values based on medium condition groups, ,file types and curvature locations).

Medium condition Groups	File Types	Apical Curve			Coronal Curve		
		Statistic	df	Sig.	Statistic	df	Sig.
Group 1	Protaper Next	0.864	10	0.086	0.853	10	0.051
	Hyflex CM	0.950	10	0.666	0.932	10	0.471
	EdgeFile	0.930	10	0.444	0.966	10	0.852
	XP endoShaper	0.843	10	0.052	0.943	10	0.586
Group 2	Protaper Next	0.940	10	0.558	0.894	10	0.187
	Hyflex CM	0.952	10	0.697	0.853	10	0.051
	EdgeFile	0.934	10	0.489	0.970	10	0.895
	XP endoShaper	0.926	10	0.413	0.936	10	0.511
Group 3	Protaper Next	0.930	10	0.446	0.974	10	0.928
	Hyflex CM	0.957	10	0.756	0.947	10	0.638
	EdgeFile	0.950	10	0.670	0.942	10	0.573
	XP endoshaper	0.911	10	0.285	0.986	10	0.988
Group 4	Protaper Next	0.902	10	0.229	0.901	10	0.226
	Hyflex CM	0.949	10	0.660	0.889	10	0.164
	EdgeFile	0.903	10	0.237	0.962	10	0.810
	XP endoShaper	0.925	10	0.401	0.962	10	0.812

A. Three-way Interaction:

A three-way ANOVA test was conducted to determine the effects of medium condition groups, file types, and curvature locations on NCF values. There was a statistically significant three-way interaction between medium condition groups, file types, and curvature locations, $p < 0.0005$ (Table 22).

Table 22. Three-way ANOVA test to determine the effects of medium condition groups, file types, and curvature locations on NCF values.

Source	Type III Sum of Squares	Mean Square	F	p
Group * File * Location	20349890	9	2261099	0.000
Error	11975039	288	41580	

B. Simple Two-way Interactions:

File types and curvature locations: There was a statistically significant simple two-way interaction between file types and curvature locations in all the four medium condition groups ($p < 0.0005$) (Table 23).

Table 23. Simple two-way interaction between file types and curvature locations on NCF values.

Treatment	Sum of Squares	Mean Square	F	Sig.
Group 1	2036705	678902	16.328	0.000
Group 2	4793634	1597878	38.429	0.000
Group 3	27263250	9087750	218.561	0.000
Group 4	41422508	13807503	332.071	0.000

C. Simple main effect of curvature locations:

No statistically significant difference was found in NCF between the apical and coronal part of canals with Protaper Next file in all four medium condition groups ($p > 0.05$) (Table 24).

For Group 1:

With Hyflex file, NCF in the coronal part (626.2 ± 126.2) was statistically significantly higher than the apical part (272.1 ± 65.2) with a mean difference of 345.1 ($p < 0.0005$), and with EdgeFile, NCF in the coronal part (1680.3 ± 250.2) was statistically significantly higher than apical part (776.6 ± 56.4) with a mean difference of 903.7 ($p < 0.0005$), and finally with XP-endoShaper file, NCF in coronal part (1479.1 ± 233.7) was statistically significantly higher than apical part (689.1 ± 90.7) with a mean difference of 790 ($p < 0.0005$) (Table 24).

For Group 2:

With Hyflex file, NCF in the coronal part (515 ± 79.8) was statistically significantly higher than the apical part (176.1 ± 67.6) with a mean difference of 338.9 ($p < 0.0005$), and with EdgeFile, NCF in the coronal part (1677.8 ± 171.2) was statistically significantly higher than apical part (329.9 ± 58.9) with a mean difference of 1348 ($p < 0.0005$), and finally with XP-endoShaper file, NCF in coronal part (840.2 ± 144.2) was statistically significantly higher than apical part (602.6 ± 120.1) with a mean difference of 237.6 ($p = 0.002$) (Table 24).

For Group 3:

With Hyflex file, NCF in the coronal part (698.3 ± 121.9) was statistically significantly higher than the apical part (175.6 ± 39) with a mean difference of 522.6 ($p < 0.0005$), and with EdgeFile, NCF in the coronal part (3456.6 ± 550) was statistically significantly higher than apical part (458.4 ± 67.2) with a mean difference of 2998.2 ($p < 0.0005$), and finally with XP-endoShaper file, NCF in coronal part (843.6 ± 56.7) was statistically significantly higher than apical part (515.7 ± 106.1) with a mean difference of 327.9 ($p < 0.0005$) (Table 24).

For Group 4:

With Hyflex file, NCF in the coronal part (921.2 ± 176.6) was statistically significantly higher than the apical part (205.1 ± 50.2) with a mean difference of 716.1 ($p < 0.0005$), and with EdgeFile, NCF in the coronal part (4170.9 ± 838.5) was statistically significantly higher than apical part (464.3 ± 67.7) with a mean difference of 3706.5 ($p < 0.0005$), and finally with XP-endoShaper file, NCF in coronal part (898.6 ± 71.3) was statistically significantly higher than apical part (517.4 ± 114.3) with a mean difference of 381.3 ($p < 0.0005$) (Table 24).

Table 24. Simple simple main effect of curvature locations on NCF values based on file types and medium condition groups.

		Apical mean (sd.)	Coronal mean (sd.)	Mean Difference	p	95% CI for Difference	
						Lower	Upper
Group 1	Protaper Next	65 (20.8)	183.1 (31.4)	-118.1	0.196	-297.6	61.4
	Hyflex CM	272.1 (65.2)	626.2 (126.2)	-354.1	0.000	-533.6	-174.6
	EdgeFile	776.6 (56.4)	1680.3 (250.2)	-903.7	0.000	-1083.2	-724.3
	XP endoShaper	689.1 (90.7)	1479.1 (233.7)	-790.0	0.000	-969.5	-610.5
Group 2	Protaper Next	50.3 (7.2)	169.1 (24.5)	-118.7	0.194	-298.2	60.8
	Hyflex CM	176.2 (67.6)	515 (79.8)	-338.9	0.000	-518.4	-159.4
	EdgeFile	329.9 (58.9)	1677.8 (171.2)	-1348.0	0.000	-1527.4	-1168.5
	XP endoShaper	602.6 (120.1)	840.2 (144.2)	-237.6	0.002	-417.1	-58.2
Group 3	Protaper Next	54 (7.2)	170.6 (25.5)	-116.6	0.202	-296.1	62.9
	Hyflex CM	175.6 (39)	698.3 (121.9)	-522.6	0.000	-702.1	-343.1
	EdgeFile	458.4 (67.2)	3456.6 (550)	-2998.2	0.000	-3177.7	-2818.8
	XP endoShaper	515.7 (106.1)	843.6 (56.7)	-327.9	0.000	-507.4	-148.4
Group 4	Protaper Next	84.4 (17.4)	234.1 (47.8)	-149.7	0.102	-329.2	29.8
	Hyflex CM	205.1 (50.2)	921.2 (176.6)	-716.1	0.000	-895.6	-536.6
	EdgeFile	464.3 (67.8)	4170.9 (838.5)	-3706.5	0.000	-3886.0	-3527.1
	XP endoShaper	517.4 (114.3)	898.6 (71.3)	-381.3	0.000	-560.8	-201.8

4.1.3. Effect of File Types, Medium Condition Groups, and Angle of Canal Curvatures on the Length of the Separated Part:

The descriptive statistics for the length of the separated part values based on medium condition groups, file types, and angle of canal curvatures are shown in the tables and graphs (Table 25, Table 26 and Figure 26).

Table 25. Descriptive statistics (Mean $\pm$ SD, Min/Max, 95% CI) of The length of the separated part values based on medium condition groups, file types, and angle of canal curvatures.

Medium Condition Groups	File Types	The Angle of Canal Curvatures	Mean (FL=mm)	Standard Deviation	Minimum	Maximum	95% CI for Mean	
							Lower	Upper
Group 1	Protaper Next	Single Curve	5.0	0.5	4.5	5.9	4.6	5.3
		Double Curve	3.1	0.1	2.9	3.4	3.0	3.2
	Hyflex CM	Single Curve	5.1	0.5	4.5	6.2	4.7	5.5
		Double Curve	3.1	0.2	2.7	3.4	2.9	3.3
	EdgeFile	Single Curve	5.2	0.3	4.7	5.7	4.9	5.4
		Double Curve	3.1	0.2	2.9	3.4	3.0	3.3
	XP endoShaper	Single Curve	5.2	0.6	4.7	6.3	4.8	5.6
		Double Curve	3.2	0.1	3.1	3.3	3.2	3.3
Group 2	Protaper Next	Single Curve	5.0	0.4	4.5	5.7	4.6	5.3
		Double Curve	3.0	0.2	2.7	3.3	2.9	3.2
	Hyflex CM	Single Curve	5.1	0.4	4.5	5.7	4.8	5.4
		Double Curve	3.1	0.1	2.9	3.3	3.0	3.2
	EdgeFile	Single Curve	5.1	0.3	4.8	5.6	4.9	5.3
		Double Curve	3.1	0.2	2.9	3.3	2.9	3.2
	XP endoShaper	Single Curve	5.2	0.3	4.8	5.6	5.1	5.4
		Double Curve	3.2	0.1	3.0	3.3	3.1	3.2
Group 3	Protaper Next	Single Curve	5.0	0.5	4.5	6.0	4.6	5.3
		Double Curve	3.1	0.1	2.8	3.2	2.9	3.2
	Hyflex CM	Single Curve	5.1	0.4	4.5	5.6	4.9	5.4

		Double Curve	3.1	0.1	2.9	3.3	3.0	3.2
		Single Curve	5.2	0.3	4.8	5.6	4.9	5.4
	EdgeFile	Double Curve	3.1	0.1	2.9	3.2	3.0	3.2
	XP endoShaper	Single Curve	5.3	0.2	4.9	5.5	5.2	5.4
		Double Curve	3.2	0.0	3.2	3.3	3.2	3.2
Group 4	Protaper Next	Single Curve	5.0	0.4	4.5	5.7	4.7	5.3
		Double Curve	3.1	0.1	2.9	3.3	3.0	3.2
	Hyflex CM	Single Curve	5.2	0.3	4.5	5.6	4.9	5.4
		Double Curve	3.1	0.1	2.9	3.2	3.0	3.2
	EdgeFile	Single Curve	5.1	0.2	4.8	5.4	5.0	5.3
		Double Curve	3.0	0.1	2.8	3.2	2.9	3.1
	XP endoShaper	Single Curve	5.3	0.3	4.8	5.7	5.0	5.5
		Double Curve	3.2	0.1	3.0	3.3	3.1	3.3

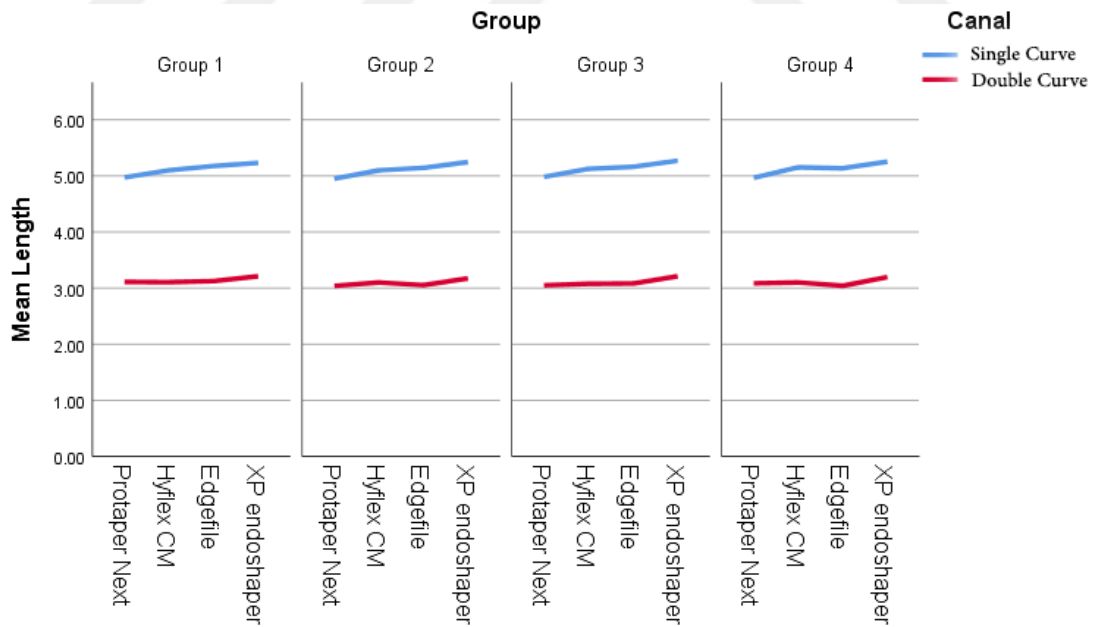


Figure 26. The line graph showed descriptive statistics of the length of the separated part values based on medium condition groups, file types, and angle of canal curvatures.

All data were normally distributed as assessed by the Shapiro-Wilk test ($p > 0.05$) (Table 26).

Table 26. Shapiro-Wilk test to determine the normality of distribution of the data (The length of the separated part values based on Medium condition groups, file types, and Angle of canal curvatures).

Medium Condition Groups	File Types	Single Curve			Double Curve		
		Statistic	df	Sig.	Statistic	df	Sig.
Group 1	Protaper Next	0.911	10	0.288	0.974	10	0.926
	Hyflex CM	0.912	10	0.293	0.915	10	0.316
	EdgeFile	0.921	10	0.369	0.929	10	0.442
	XP endoShaper	0.874	10	0.066	0.926	10	0.412
Group 2	Protaper Next	0.922	10	0.374	0.921	10	0.366
	Hyflex CM	0.903	10	0.238	0.914	10	0.313
	EdgeFile	0.939	10	0.538	0.908	10	0.268
	XP endoShaper	0.946	10	0.617	0.896	10	0.197
Group 3	Protaper Next	0.894	10	0.190	0.902	10	0.233
	Hyflex CM	0.953	10	0.705	0.944	10	0.599
	EdgeFile	0.891	10	0.175	0.974	10	0.923
	XP endoShaper	0.936	10	0.508	0.904	10	0.239
Group 4	Protaper Next	0.957	10	0.746	0.894	10	0.190
	Hyflex CM	0.914	10	0.312	0.849	10	0.056
	EdgeFile	0.885	10	0.149	0.884	10	0.147
	XP endoShaper	0.963	10	0.823	0.853	10	0.063

A. Three-way Interaction:

A three-way ANOVA test was conducted to determine the effects of medium condition groups, file types, and angle of canal curvatures on the length of the separated part values. There was no statistically significant three-way interaction between medium condition groups, file types, and angle of canal curvatures, $p = 1.000$. Also, there was no

two-way interaction either between group * file ($p = 1.000$), group * canal ($p = 0.956$), or file * canal (0.194) (Table 27).

Table 27. Three-way ANOVA test to determine the effects of medium condition groups, file types, and angle of canal curvatures on the length of the separated part values.

Source	Type III Sum of Squares	Mean Square	F	p
Group * File	0.054	0.006	0.073	1.000
Group * Canal	0.026	0.009	0.107	0.956
File * Canal	0.389	0.130	1.581	0.194
Group * File * Canal	0.016	0.002	0.022	1.000
Error	23.601	0.082		

B. The main effect of medium condition groups:

A one-way ANOVA test was conducted to determine the effect of the medium condition groups on the length of the separated part values. Data are presented as mean $\pm$ standard deviation. The length of the separated part was 4.6 ± 1.1 mm in all the four groups (Table 28). No statistically significant difference was found between these groups, $p = 1.000$ (Table 29).

Table 28. The length of the separated part values based on medium condition groups (In both angle of the canal curvatures).

Medium Condition Groups	Mean (FL=mm)	Standard Deviation	Minimum	Maximum	95% CI for Mean	
					Lower	Upper
Group 1	4.6	1.1	2.7	6.3	4.4	4.8
Group 2	4.6	1.1	2.7	6.1	4.4	4.8
Group 3	4.6	1.1	2.8	6.2	4.4	4.8
Group 4	4.6	1.1	2.8	6.2	4.4	4.8

Table 29. One-way ANOVA results for the main effect of medium condition groups on the length of the separated part values (In both angle of the canal curvatures).

	Sum of Squares	Mean Square	F	p
Between Groups	0.016	0.005	0.004	1.000
Within Groups	614.646	1.291		
Total	614.661			

C. The main effect of file types:

A one-way ANOVA test was conducted to determine the effect of a file type on the length of the separated part values. Data are presented as mean $\pm$ standard deviation. The length of the separated part was 4.6 ± 1.1 mm in Protaper Next, Hyflex CM, and EdgeFile and 4.7 ± 1.1 mm in XP-endoShaper (Table 30). No statistically significant difference was found between these groups, $p = 0.744$ (Table 31).

Table 30. The length of the separated part values based on the file types (In both angle of the canal curvatures).

File Types	Mean (FL=mm)	Standard Deviation	Minimum	Maximum	95% CI for Mean	
					Lower	Upper
Protaper Next	4.6	1.1	2.7	6.2	4.4	4.8
Hyflex CM	4.6	1.1	2.7	6.2	4.4	4.8
EdgeFile	4.6	1.1	2.8	5.9	4.4	4.8
XP endoShaper	4.7	1.1	3.0	6.3	4.5	4.9

Table 31. One-way ANOVA results for the main effect of file types on the length of separated part values (In both angle of canal curvatures).

	Sum of Squares	Mean Square	F	Sig.
Between Groups	1.597	0.532	0.413	0.744
Within Groups	613.065	1.288		
Total	614.661			

D. The main effect of angle of canal curvatures:

An independent samples t-test was conducted to determine the effect of the angle of canal curvatures on the length of the separated part values. Data are presented as mean $\pm$ standard deviation. The length of the separated part in single curve canals (5.1 ± 0.4 mm) was higher than double curve canals (3.1 ± 0.1 mm) a statistically significant difference of 2 mm was found between these two groups, $p < 0.0005$ (Table 32 and Table 33).

Table 32. The length of the separated part values based on the angle of canal curvatures.

The angle of Canal Curvature	Mean	Standard Deviation	Minimum	Maximum	95% CI for Mean	
					Lower	Upper
Single Curve	5.1	0.4	4.5	6.3	5.1	5.2
Double Curve	3.1	0.1	2.7	3.4	3.1	3.1

Table 33. Independent samples t-test for the main effect of angle of the canal curvatures on the length of the separated part values.

	t	Sig. (2-tailed)	Mean Difference	95% Confidence Interval of the Difference	
				Lower	Upper
Length of the separated part	63.186	0.000	2.0	1.9	2.1

4.1.4. Effect of File Types, Medium Condition Groups, and Curvature Locations on the Length of the Separated Part:

The descriptive statistics for the length of the separated part values depending on medium condition groups, file types, and curvature locations are shown in the tables and graphs (Table 34, Table 35 and Figure 27).

Table 34. Descriptive statistics (Mean $\pm$ SD, Min/Max, 95% CI) of The length of the separated part values based on medium condition groups, file types, and place of curvature locations.

Medium Condition Groups	File Type	Curvature Locations	Mean (FL=mm)	Standard Deviation	Minimum	Maximum	95% CI for Mean	
							Lower	Upper
Group 1	Protaper Next	Apical	3.1	0.1	2.9	3.4	3.0	3.2
		Coronal	5.6	0.4	5.0	6.2	5.3	5.9
	Hyflex CM	Apical	3.1	0.2	2.7	3.4	2.9	3.3
		Coronal	5.6	0.2	5.3	5.9	5.5	5.7
	EdgeFile	Apical	3.1	0.2	2.9	3.4	3.0	3.3
		Coronal	5.6	0.3	5.0	5.9	5.4	5.8
	XP endoShaper	Apical	3.2	0.1	3.1	3.3	3.2	3.3
		Coronal	5.7	0.2	5.4	6.0	5.6	5.8
Group 2	Protaper Next	Apical	3.0	0.2	2.7	3.3	2.9	3.2
		Coronal	5.7	0.2	5.5	6.0	5.6	5.8
	Hyflex CM	Apical	3.1	0.1	2.9	3.3	3.0	3.2
		Coronal	5.6	0.2	5.4	5.9	5.5	5.8
	EdgeFile	Apical	3.1	0.2	2.9	3.3	2.9	3.2
		Coronal	5.7	0.2	5.4	5.9	5.5	5.8
	XP endoShaper	Apical	3.2	0.1	3.0	3.3	3.1	3.2
		Coronal	5.7	0.2	5.4	6.1	5.6	5.9
Group 3	Protaper Next	Apical	3.1	0.1	2.8	3.2	2.9	3.2
		Coronal	5.7	0.3	5.0	6.1	5.4	5.9
	Hyflex CM	Apical	3.1	0.1	2.9	3.3	3.0	3.2
		Coronal	5.7	0.2	5.4	6.2	5.5	5.8
	EdgeFile	Apical	3.1	0.1	2.9	3.2	3.0	3.2
		Coronal	5.7	0.2	5.3	5.9	5.5	5.8
	XP endoShaper	Apical	3.2	0.0	3.2	3.3	3.2	3.2
		Coronal	5.7	0.3	5.2	6.1	5.5	6.0
Group 4	Protaper Next	Apical	3.1	0.1	2.9	3.3	3.0	3.2
		Coronal	5.6	0.4	5.0	6.1	5.4	5.9
	Hyflex CM	Apical	3.1	0.1	2.9	3.2	3.0	3.2

	EdgeFile	Coronal	5.6	0.3	5.4	6.2	5.4	5.8
		Apical	3.0	0.1	2.8	3.2	2.9	3.1
		Coronal	5.7	0.2	5.4	5.9	5.6	5.8
	XP endoShaper	Apical	3.2	0.1	3.0	3.3	3.1	3.3
		Coronal	5.7	0.3	5.2	6.2	5.5	6.0

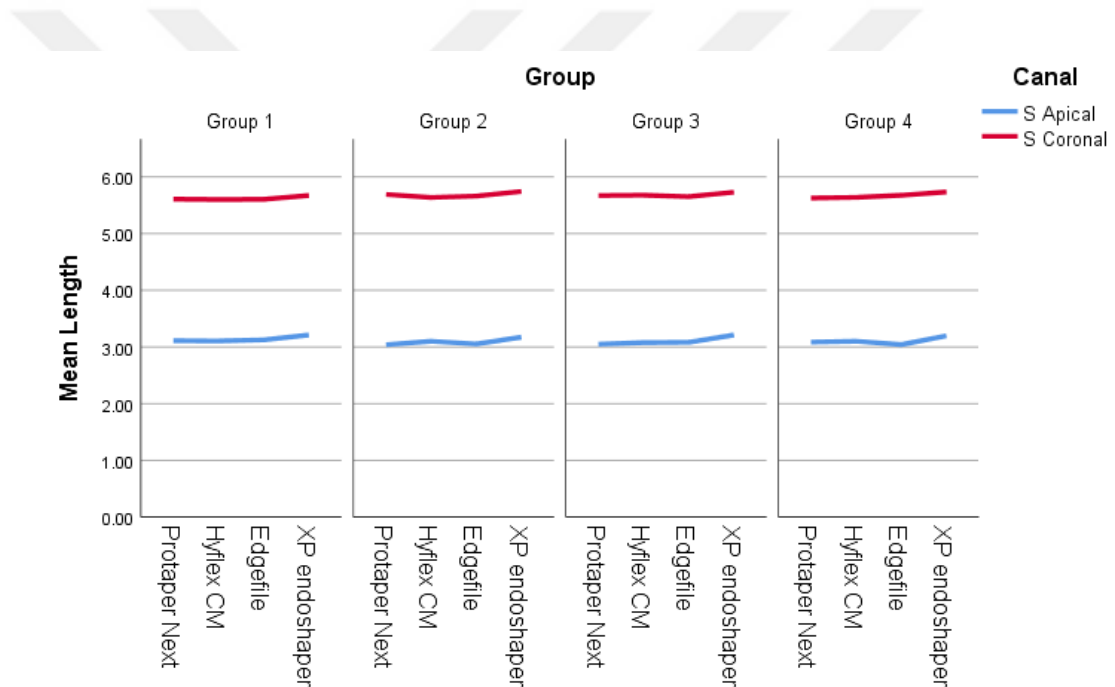


Figure 27. The line graph showed descriptive statistics the length of the separated part values based on medium condition groups, file types, and curvature locations.

All data were normally distributed as assessed by the Shapiro-Wilk test ($p > 0.05$) (Table 35).

Table 35. Shapiro-Wilk test to determine the normality of distribution of the data (The length of the separated part values based on medium condition groups, file types , and curvature locations).

Medium Condition Groups	File Types	Apical Curve			Coronal Curve		
		Statistic	df	Sig.	Statistic	df	Sig.
Group 1	Protaper Next	0.974	10	0.926	0.970	10	0.894
	Hyflex CM	0.915	10	0.316	0.944	10	0.597
	EdgeFile	0.929	10	0.442	0.849	10	0.056
	XP endoShaper	0.926	10	0.412	0.987	10	0.992
Group 2	Protaper Next	0.921	10	0.366	0.969	10	0.886
	Hyflex CM	0.914	10	0.313	0.849	10	0.056
	EdgeFile	0.908	10	0.268	0.950	10	0.672
	XP endoShaper	0.896	10	0.197	0.954	10	0.713
Group 3	Protaper Next	0.902	10	0.233	0.960	10	0.783
	Hyflex CM	0.944	10	0.599	0.875	10	0.115
	EdgeFile	0.974	10	0.923	0.955	10	0.728
	XP endoShaper	0.904	10	0.239	0.920	10	0.354
Group 4	Protaper Next	0.894	10	0.190	0.961	10	0.797
	Hyflex CM	0.849	10	0.056	0.862	10	0.058
	EdgeFile	0.884	10	0.147	0.906	10	0.256
	XP endoShaper	0.853	10	0.063	0.925	10	0.396

A. Three-way Interaction:

A three-way ANOVA test was conducted to determine the effects of medium condition groups, file types, and curvature locations on the length of the separated part values. There was no statistically significant three-way interaction between medium condition groups, file types, and curvature locations, $p = 0.997$. Also, there was no two-way interaction either between group * file ($p = 1.000$), group * location ($p = 0.342$), or file * location (0.806) (Table 36).

Table 36. Three-way ANOVA test to determine the effects of medium condition groups, file types, and curvature locations on the length of the separated part values.

Source	Type III Sum of Squares	Mean Square	F	p
Group * File	0.010	0.001	0.025	1.000
Group * Location	0.142	0.047	1.119	0.342
File * Location	0.041	0.014	0.327	0.806
Group * File * Location	0.063	0.007	0.165	0.997
Error	12.170	0.042		

B. The main effect of medium condition groups:

A one-way ANOVA test was conducted to determine the effect of the medium condition groups on the length of the separated part values. Data are presented as mean $\pm$ standard deviation. The length of the separated part was 4.4 ± 1.3 mm in all the four groups (Table 37). No statistically significant difference was found between these groups, $p = 1.000$ (Table 38).

Table 37. The length of the separated part values based on medium condition groups (In both of curvature locations).

Medium Condition groups	Mean (FL=mm)	Standard Deviation	Minimum	Maximum	95% CI for Mean	
					Lower	Upper
Group 1	4.4	1.3	2.7	6.2	4.1	4.7
Group 2	4.4	1.3	2.7	6.1	4.1	4.7
Group 3	4.4	1.3	2.8	6.2	4.1	4.7
Group 4	4.4	1.3	2.8	6.2	4.1	4.7

Table 38. One-way ANOVA results for the main effect of the medium condition groups on the separated part values (In both of curvature locations).

	Sum of Squares	Mean Square	F	p
Between Groups	0.008	0.003	0.002	1.000
Within Groups	534.410	1.691		
Total	534.419			

C. The main effect of file types:

A one-way ANOVA test was conducted to determine the effect of a file type on the length of the separated part values. Data are presented as mean $\pm$ standard deviation. The length of the separated part was 4.4 ± 1.3 mm in Protaper Next, Hyflex CM, and EdgeFile and 4.5 ± 1.3 mm in XP-endoShaper (Table 39). No statistically significant difference was found between these groups, $p = 0.954$ (Table 40).

Table 39. The length of the separated part values based on the file types (In both of curvature locations).

File Types	Mean (FL=mm)	Standard Deviation	Minimum	Maximum	95% CI for Mean	
					Lower	Upper
Protaper Next	4.4	1.3	2.7	6.2	4.1	4.7
Hyflex CM	4.4	1.3	2.7	6.2	4.1	4.7
EdgeFile	4.4	1.3	2.8	5.9	4.1	4.7
XP endoShaper	4.5	1.3	3.0	6.2	4.2	4.7

Table 40. One-way ANOVA results for the main effect of file types on the separated length values (In both of curvature locations).

	Sum of Squares	Mean Square	F	Sig.
Between Groups	0.560	0.187	0.110	0.954
Within Groups	533.859	1.689		
Total	534.419			

D. The main effect of the curvature locations:

An independent samples t-test was conducted to determine the effect of curvature locations on the length of the separated part values. Data are presented as mean $\pm$ standard deviation. The length of the separated part in the coronal curve (5.7 ± 0.2 mm) was higher

than the apical curve (3.1 ± 0.1 mm) a statistically significant difference of 2.6 mm was found between these two groups, $p < 0.0005$ (Table 41 and Table 42).

Table 41. The length of the separated part values based on curvature locations.

Curvature Locations	Mean	Standard Deviation	Minimum	Maximum	95% CI for Mean	
					Lower	Upper
Apical Curve	3.1	0.1	2.7	3.4	3.1	3.1
Coronal Curve	5.7	0.2	5.0	6.2	5.6	5.7

Table 42. Independent samples t-test for the main effect of curvature locations.

	t	Sig. (2-tailed)	Mean Difference	95% Confidence Interval of the Difference	
				Lower	Upper
Length of the separated part	112.964	0.000	2.6	2.5	2.6

4.1.5. Scanning Electron Microscope Analysis:

Scanning electron microscopy longitudinal view of the analysis of the separated instruments of each group (at 250x magnification) revealed manufacturing grooves, microcracks, and disruption of the cutting edges (due to metal rollover) in all samples (Figure 28, Figure 30, Figure 32, and Figure 34). Fractographic Scanning electron microscopy views of the fractured surface presented typical features of cyclic fatigue failure for all instruments. The fracture surfaces of all brands revealed similar fractographic features. SEM analysis at 500X exhibited different planes on a fracture surface in all brands demonstrating multiple crack origins (Figure 29, Figure 31, Figure 33, and Figure 35). All instruments presented a mechanical characteristic of ductile fracture surfaces were observed under high magnification at 5000X and that shows fatigue striations that are characteristic of cyclic fatigue fracture, with microvoids, dimples areas, and along with dimples and microvoids exhibited crater-like formations in Hyflex CM files (Figure 29, Figure 31, Figure 33, and Figure 35).

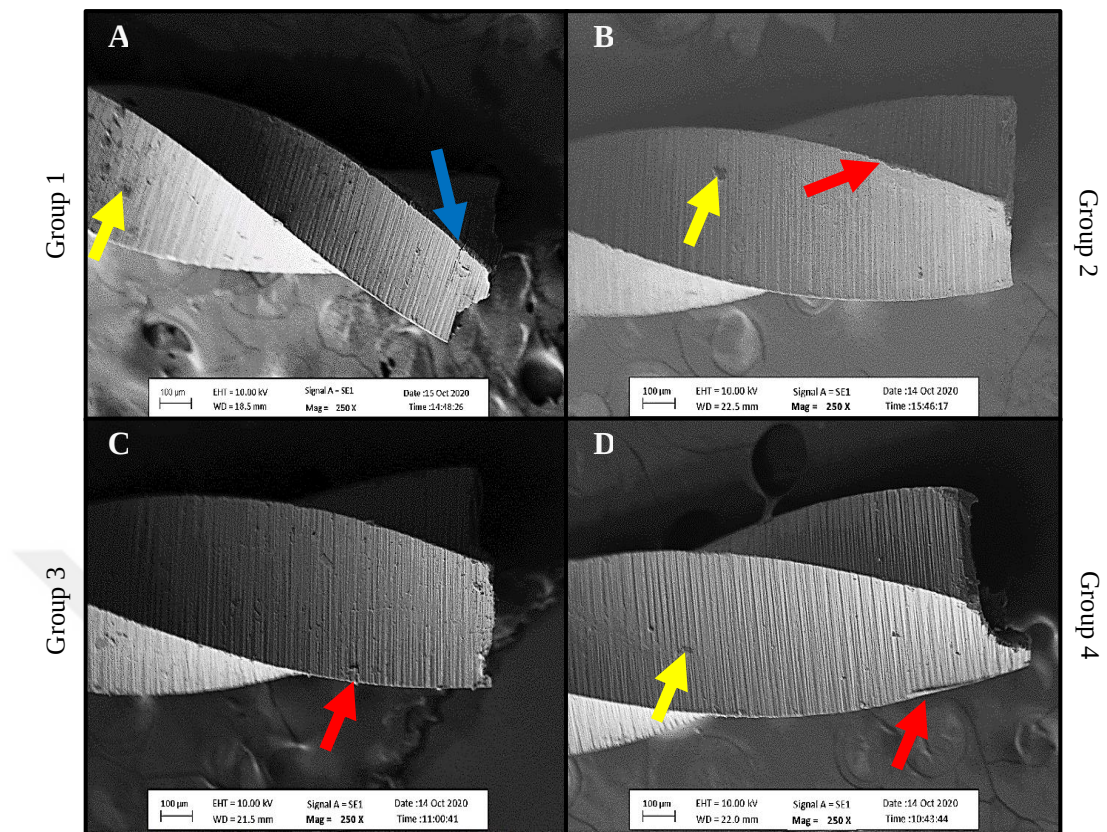


Figure 28. Longitudinal SEM images for view fractured Protaper Next rotary files at a magnification of 250X and showing back scattered micrograph of fracture site with irregular cracks near to fracture site (*blue arrow*), disruption of the cutting edges, grooves and surface pitting (*red arrows*), and debris (*yellow arrows*).

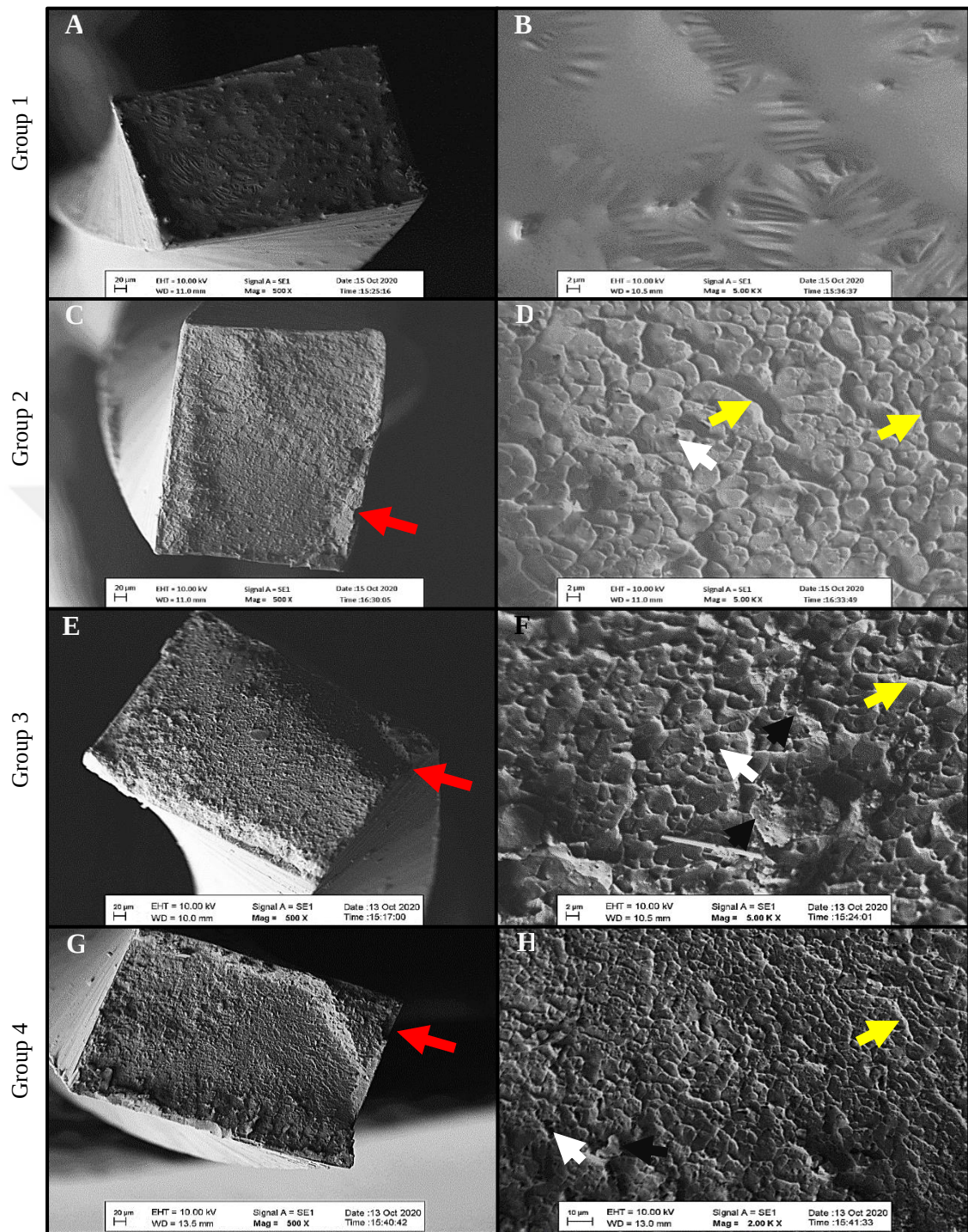


Figure 29. Representative scanning electron microscopy images showing cross-sections of fractured Protaper Next instruments after cyclic fatigue. Left column (A, C, E, and G) at lower magnification; 500X view of fracture surfaces of the test instruments showed the crack initiation origin (red arrows). Right column (B, D, F, and H)) at higher magnification; 5000X view of dimpled areas covered almost all the cross-section areas with the characteristic surface pattern of fatigue failure. Presence of fatigue striations (yellow arrows), microvoids (white arrows), inclusions (black arrow). Ductile fracture roughness was evidence in all the samples (A to H).

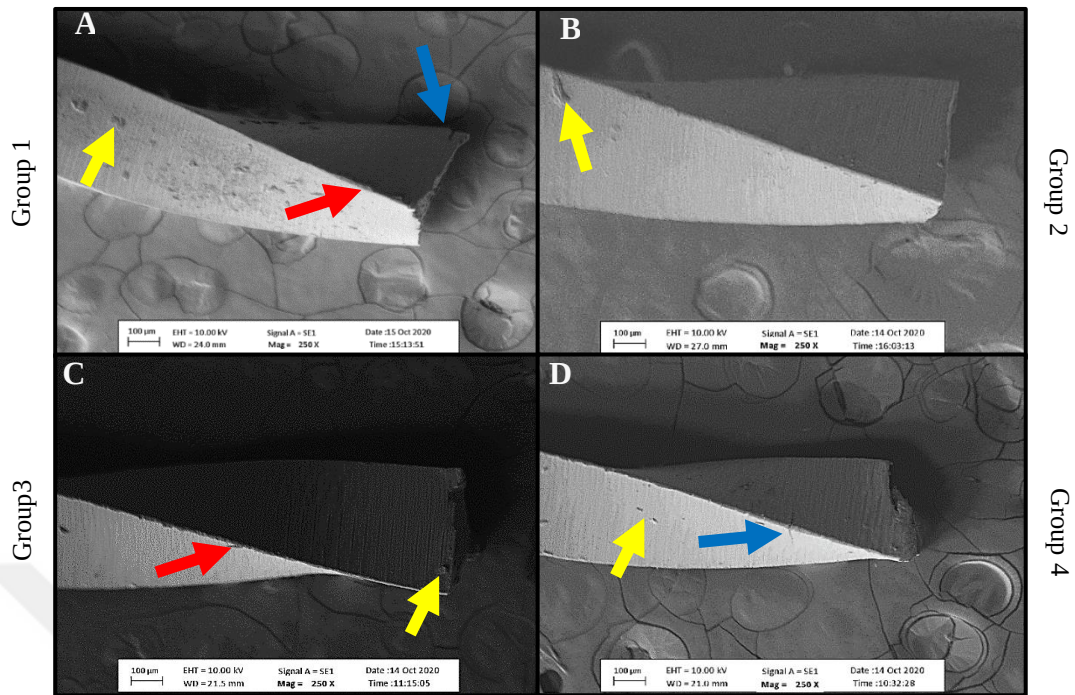


Figure 30. Longitudinal SEM images for view fractured Hyflex CM rotary files at a magnification of 250X and showing back scattered micrograph of fracture site with irregular cracks near to fracture site (*blue arrows*), disruption of the cutting edges, grooves and surface pitting (*red arrows*), and debris (*yellow arrows*).

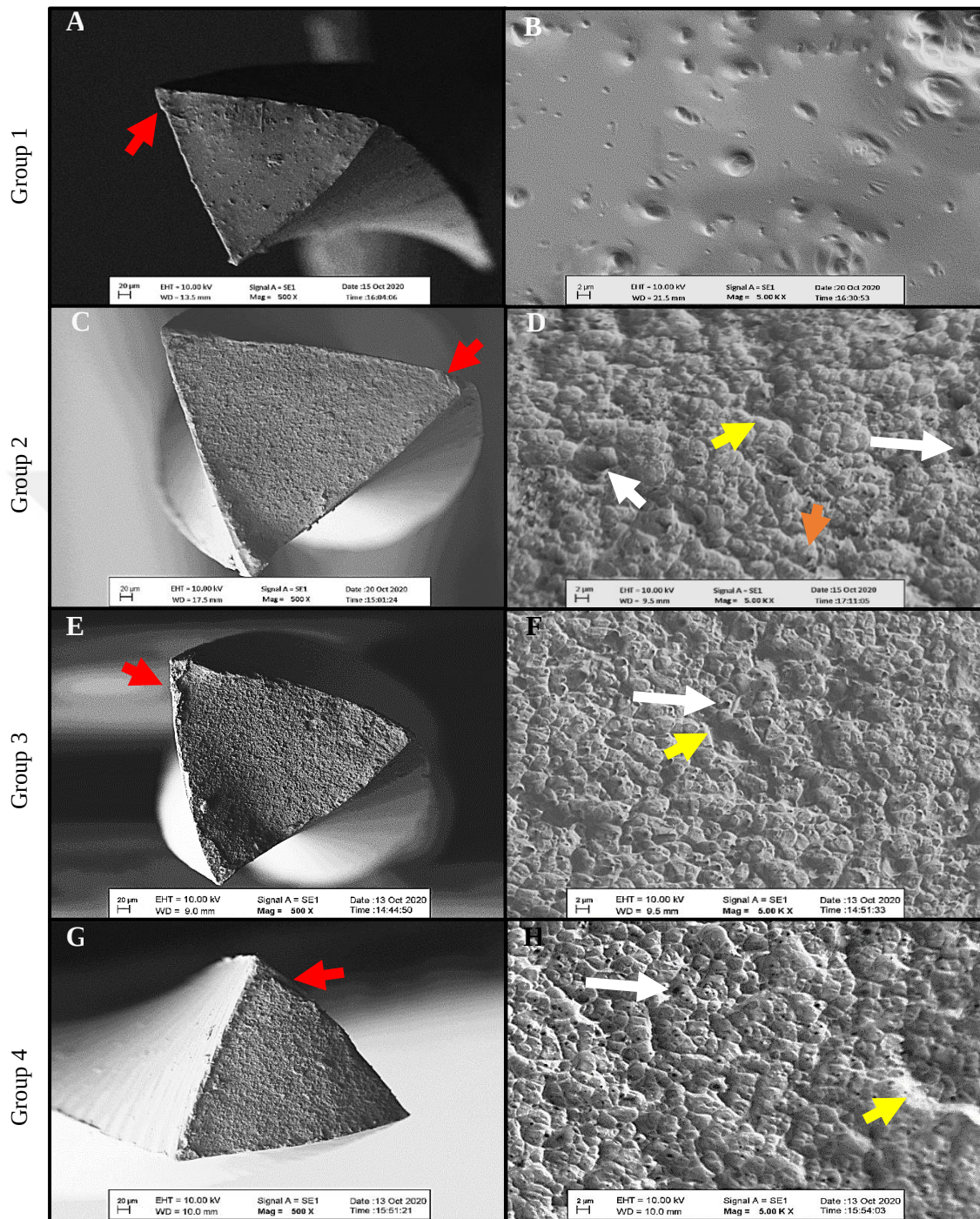


Figure 31. Representative scanning electron microscopy images showing cross-sections of fractured Hyflex CM instruments after cyclic fatigue. Left column (A, C, E, and G) at lower magnification; 500X view of fracture surfaces of the test instruments showed the crack initiation origin (red arrows). Right column (B, D, F, and H)) at higher magnification; 5000X view of dimpled areas covered all cross-section areas with the characteristic surface pattern of fatigue failure. Presence of fatigue striations (yellow arrows), microvoids (white arrows), crater-like formation (orange arrow). Ductile fracture roughness was evidence in all the samples (A to H).

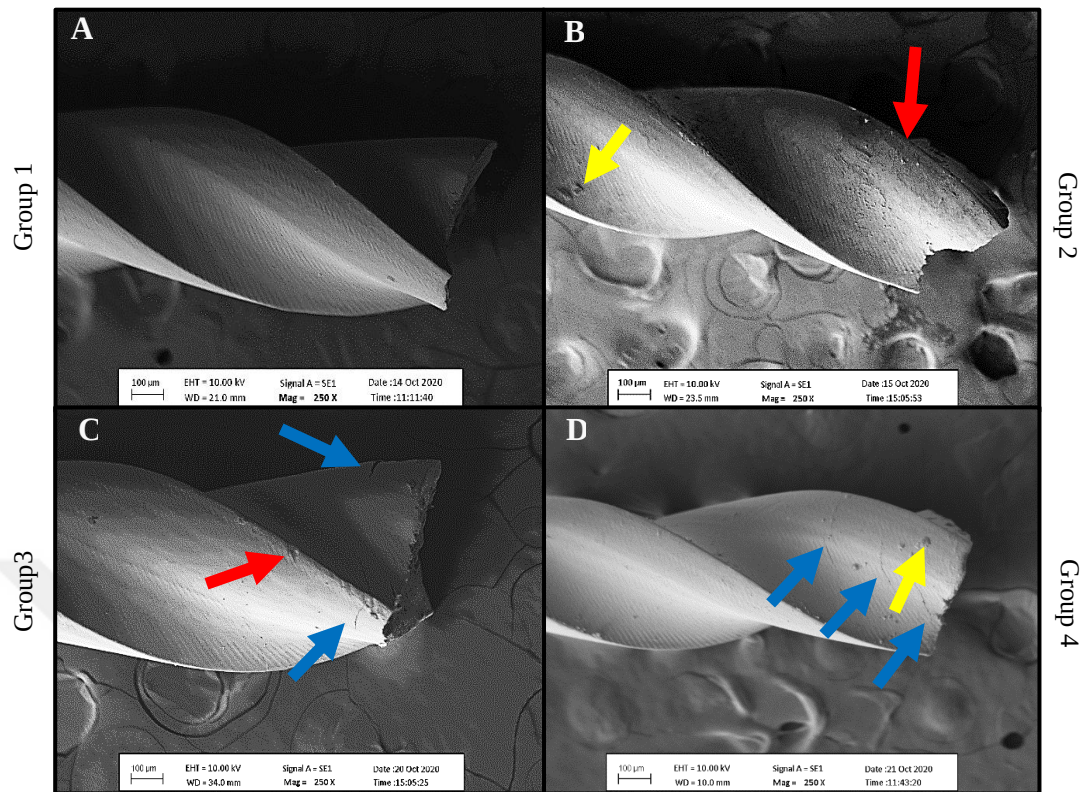


Figure 32. Longitudinal SEM images for view fractured EdgeFile rotary files at a magnification of 250X and showing back scattered micrograph of fracture site with irregular cracks near to fracture site (*blue arrows*), disruption of the cutting edges, grooves and surface pitting (*red arrows*), debris (*yellow arrows*).

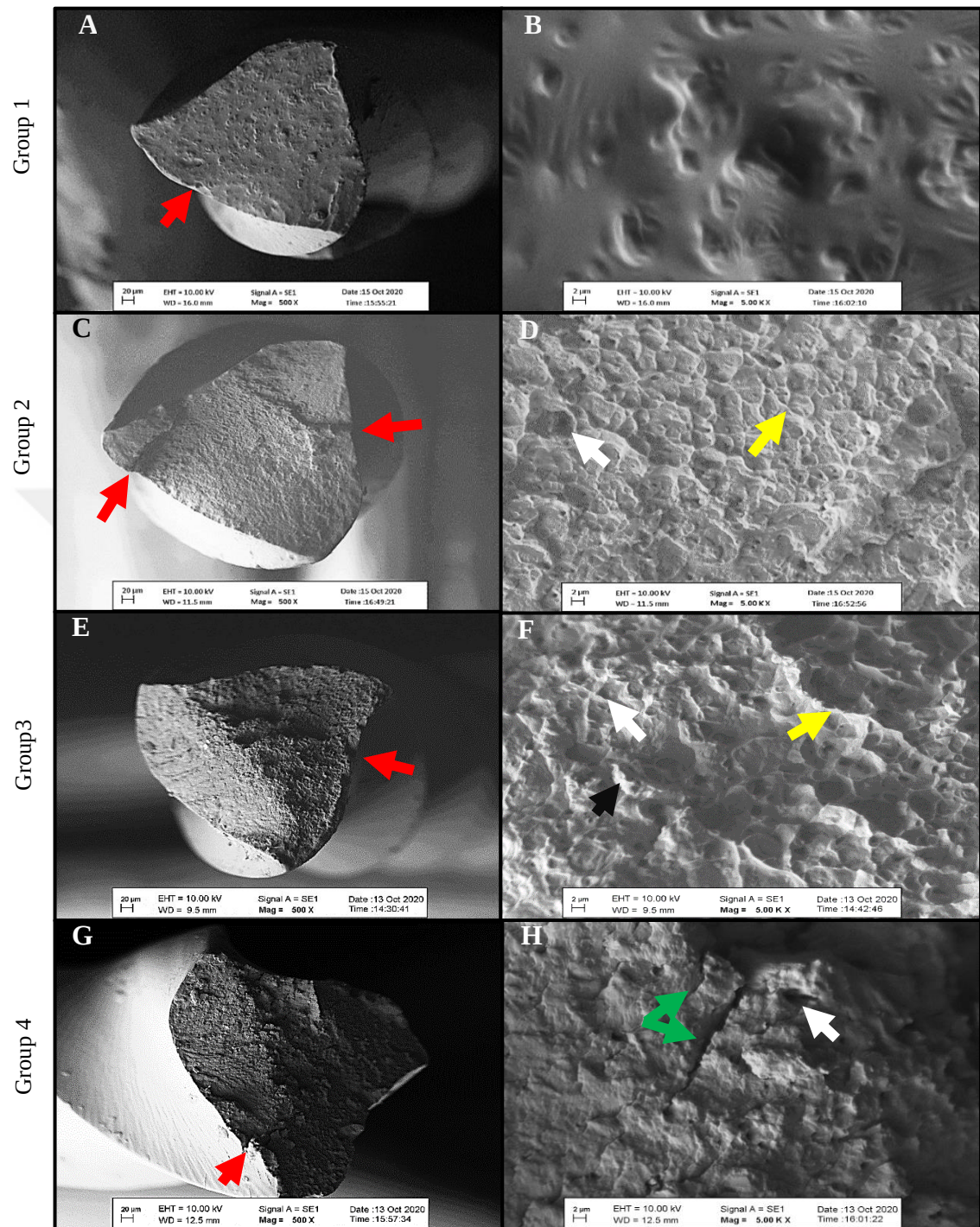


Figure 33. Representative scanning electron microscopy images showing cross-sections of fractured EdgeFile instruments after cyclic fatigue. Left column (A, C, E, and G) at lower magnification; 500X view of fracture surfaces of the test instruments showed the crack initiation origin (red arrows). Right column (B, D, F, and H)) at higher magnification; 5000X view of centralized dimpled areas with the characteristic surface pattern of fatigue failure. Presence of fatigue striations (yellow arrows), microvoids (white arrows), inclusions (black arrow), and multiple surface micro-cracking (green arrows). Ductile fracture roughness was evidence in all the samples (A to H).

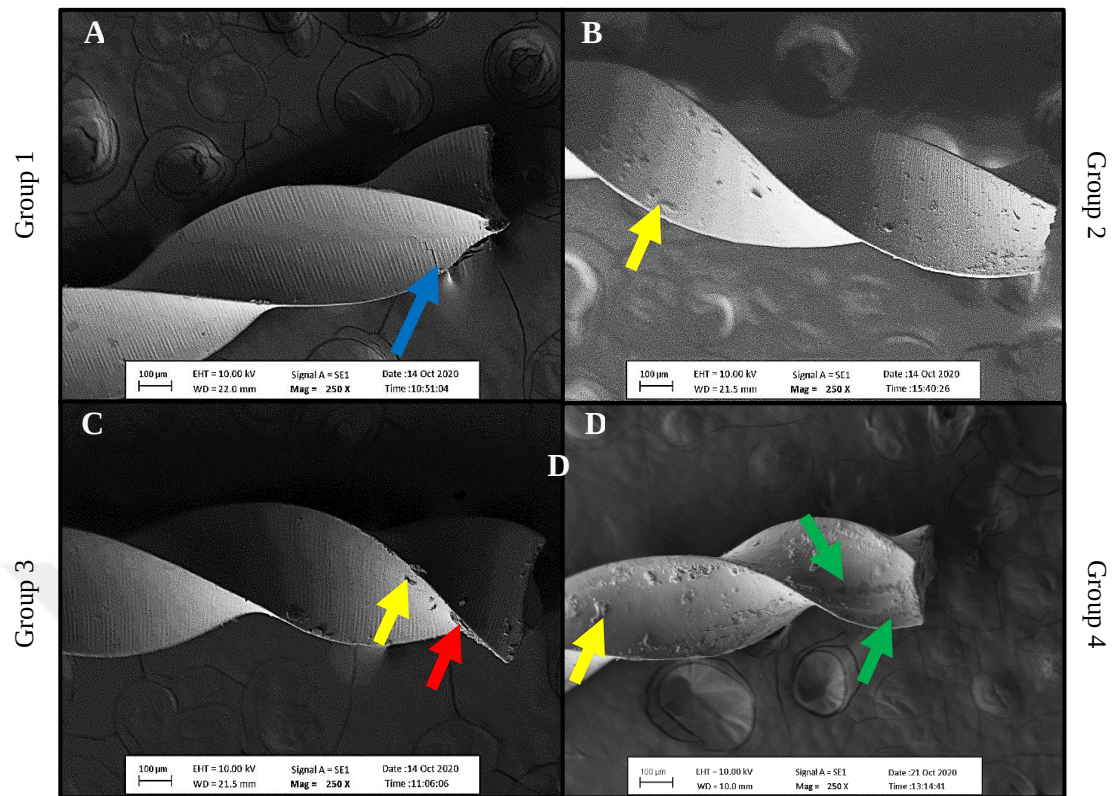


Figure 34. Longitudinal SEM images for view fractured XP-endoShaper rotary files at a magnification of 250X and showing back scattered micrograph of fracture site with irregular cracks near to fracture site (*blue arrow*), disruption of the cutting edges, grooves and surface pitting (*red arrow*), corrosion (*green arrows*), and debris (*yellow arrows*).

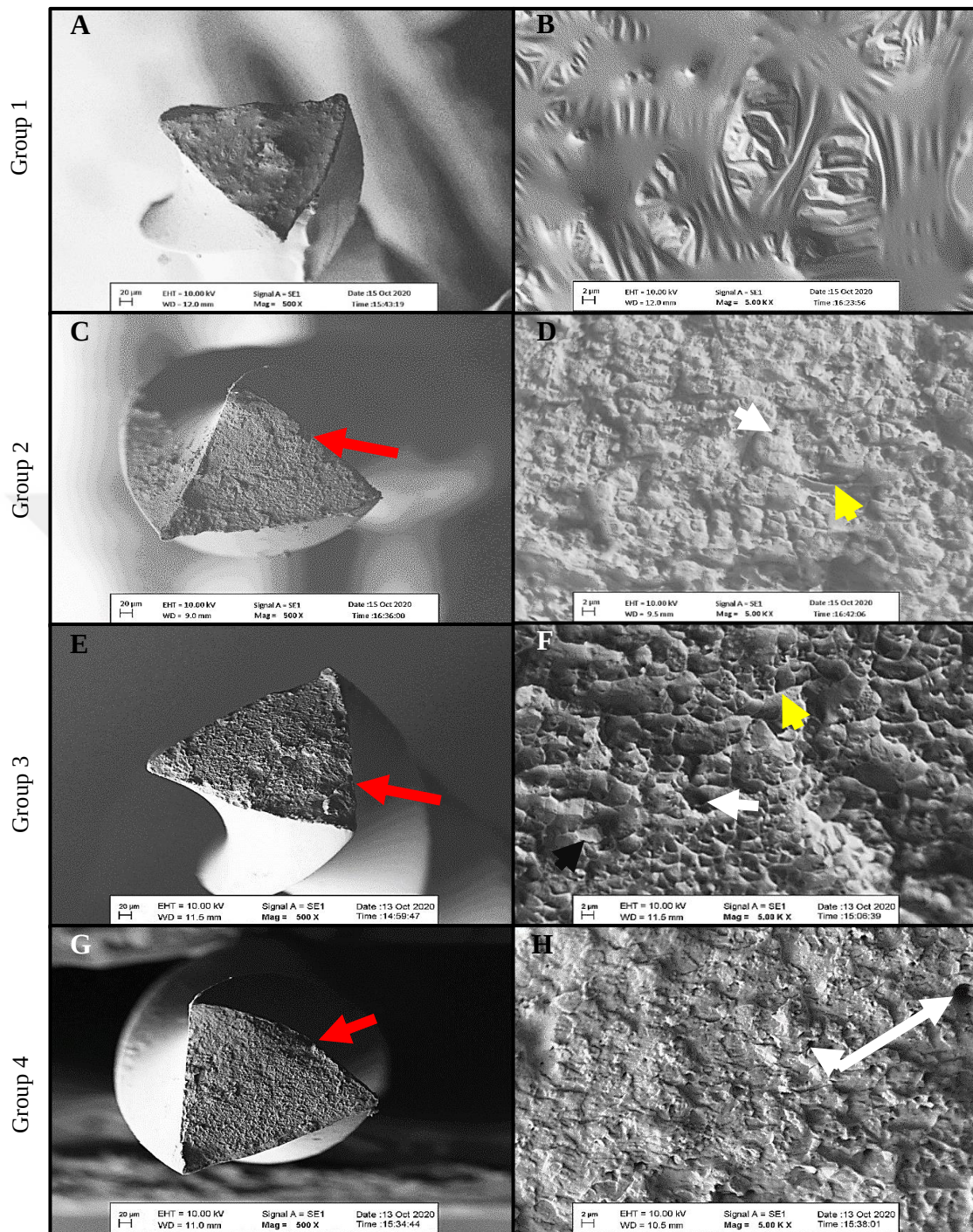


Figure 35. Representative scanning electron microscopy images showing cross-sections of fractured XP endoShaper instruments after cyclic fatigue. Left column (A, C, E, and G) at lower magnification; 500X view of fracture surfaces of the test instruments showed the crack initiation origin (*red arrows*). Right column (B, D, F, and H)) at higher magnification; 5000X view of dimpled areas covered all the cross-section areas with the characteristic surface pattern of fatigue failure. Presence of fatigue striations (*yellow arrows*), microvoids (*white arrows*), inclusions (*black arrow*). Ductile fracture roughness was evidence in all the samples (A to H).

4. 2. Results of Bending Resistance Test:

The descriptive statistics for bending resistance based on file types are shown in the tables and graphs (Table 43, Table 44, and Figure 36).

Table 43. Descriptive statistics (Mean $\pm$ SD, Min/Max, 95% CI) for bending resistance based on the file types.

File Types	Mean (GF)	Standard Deviation	Minimum	Maximum	95% CI for Mean	
					Lower	Upper
Protaper Next	133.5	20.4	102.6	170.2	124.0	143.0
Hyflex CM	101.5	12.6	80.0	130.4	95.6	107.4
EdgeFile	56.1	10.0	43.9	74.7	51.4	60.7
XP endoShaper	48.7	5.4	39.1	59.4	46.1	51.2

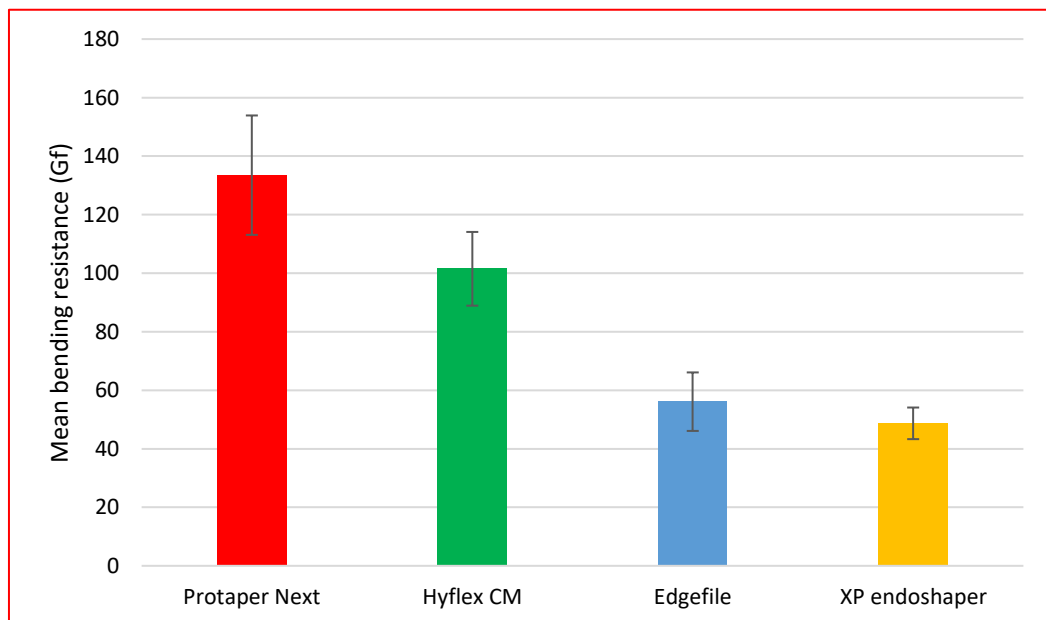


Figure 36. Bar chart comparison of bending resistance based on the file types.

All data were normally distributed as assessed by the Shapiro-Wilk test ($p > 0.05$) (Table 44).

Table 44. Shapiro-Wilk test to determine the normality of distribution of the data (Bending resistance values based on file types).

File	Statistic	df	Sig.
Protaper Next	.930	20	.156
Hyflex CM	.975	20	.861
EdgeFile	.915	20	.079
XP endoShaper	.975	20	.852

A **one-way Welch ANOVA** tests were conducted to determine if bending resistance was different between the file type groups, as there was heterogeneity of variances when assessed by Levene's test of homogeneity of variances ($p < .0005$). Data are presented as mean $\pm$ standard deviation.

Bending resistance was statistically significantly different between different file type groups, Welch's $F = 183.013$, $p < .0005$ (Table 45). Bending resistance increased from XP-endoShaper ($48.7 \pm 5.4\text{gf}$) to EdgeFile ($56.1 \pm 10\text{gf}$) to Hyflex CM ($101.5 \pm 12.6\text{gf}$) to Protaper Next ($133.5 \pm 20.4\text{gf}$) types file, in that order. Games-Howell post hoc analysis revealed that bending resistance with XP-endoShaper file was lower than each of Protaper Next file by (84.9, 95% CI, 71.8 to 98gf), Hyflex CM by (52.9, 95% CI, 44.4 to 61.3gf), and EdgeFile file by (7.4, 95% CI, 0.5 to 14.3gf) with a statistically significant difference ($p < 0.05$). Also, bending resistance with EdgeFile was lower than each of Protaper Next file by (77.5, 95% CI, 63.6 to 91.3gf), and Hyflex CM by (45.5, 95% CI, 35.8 to 55.1gf) with a statistically significant difference ($p < .0005$). Finally, bending resistance with Hyflex CM was lower than Protaper Next file by (32, 95% CI, 17.5 to 46.5gf) with a statistically significant difference ($p < .0005$) (Table 46).

Table 45. One-way Welch's ANOVA results for the effect of file types on bending resistance.

	Welch's F	Sig.
Between Groups	183.013	.000

Table 46. Games-Howell post hoc analysis for pairwise comparisons of bending resistance between file types.

		Mean Difference	p	95% CI for Difference	
				Lower	Upper
Protaper Next	Hyflex CM	32.0	0.000	17.5	46.5
	EdgeFile	77.5	0.000	63.6	91.3
	XP endoShaper	84.9	0.000	71.8	98.0
Hyflex CM	EdgeFile	45.5	0.000	35.8	55.1
	XP endoShaper	52.9	0.000	44.4	61.3
EdgeFile	XP endoShaper	7.4	0.033	0.5	14.3

4. 3. Results of Microhardness Test:

The descriptive statistics for Vickers microhardness based on file types are shown in the tables and graphs (Table 47, Table 48, and Figure 37).

Table 47. Descriptive statistics (Mean $\pm$ SD, Min/Max, 95% CI) for Vickers microhardness based on the file types.

File Types	Mean (VHN)	Standard Deviation	Minimum	Maximum	95% CI for Mean	
					Lower	Upper
Protaper Next	463.3	11.2	445.9	483.8	458.1	468.5
Hyflex CM	354.3	5.9	341.6	365.3	351.5	357.0
EdgeFile	456.2	8.1	442.1	466.8	452.4	460.0
XP endoShaper	424.5	7.1	409.3	435.5	421.2	427.8

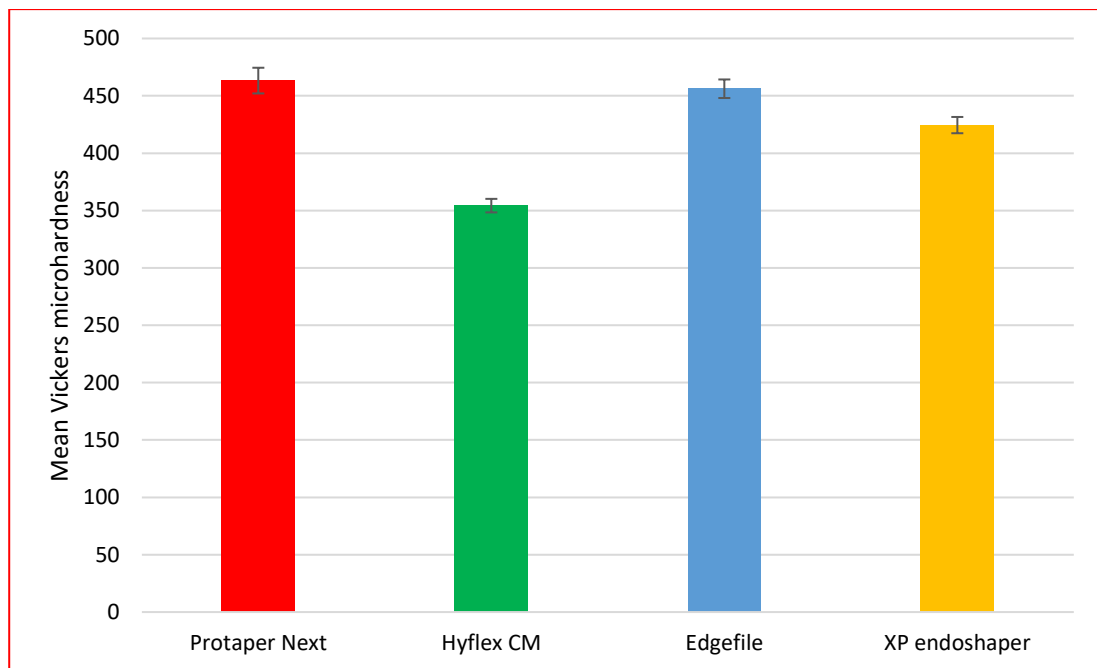


Figure 37. Bar chart comparisons of Vickers microhardness based on the file types.

All data were normally distributed as assessed by the Shapiro-Wilk test ($p > 0.05$) (Table 48).

Table 48. Shapiro-Wilk test to determine the normality of distribution of the data (VHN values based on file types).

File	Statistic	df	Sig.
Protaper Next	.963	20	.600
Hyflex CM	.963	20	.597
EdgeFile	.922	20	.109
XP endoShaper	.970	20	.746

A **one-way Welch ANOVA** tests were conducted to determine if Vickers microhardness was different between the file type groups, as there was heterogeneity of variances when assessed by Levene's test of homogeneity of variances ($p = .009$). Data are presented as mean $\pm$ standard deviation.

Microhardness was statistically significantly different between different file type groups, Welch's $F = 953.665$, $p < .0005$ (Table 49). Vickers microhardness increased from Hyflex CM (345.3 ± 5.9) to XP-endoShaper (424.5 ± 7.1) to EdgeFile (456.2 ± 8.1) to Protaper Next (463.3 ± 11.2) types file, in that order. Games-Howell post hoc analysis revealed that Vickers microhardness with Hyflex CM file was lower than each of Protaper Next file by (109.1, 95% CI, 101.3 to 116.8), EdgeFile by (101.9, 95% CI, 95.9 to 108), and XP-endoShaper file by (70.2, 95% CI, 64.7 to 75.8) with a statistically significant difference ($p < .0005$). Also, Vickers microhardness with XP-endoShaper was fewer than each of Protaper Next file by (38.8, 95% CI, 30.8 to 46.8), and EdgeFile by (31.7, 95% CI, 25.2 to 38.2) with a statistically significant difference ($p < .0005$). However, there was no statistically significant difference in Vickers microhardness between Protaper Next and EdgeFile, $p = 0.116$ (Table 50).

Table 49. One-way Welch's ANOVA results for the effect of file types on microhardness.

	Welch's F	Sig.
Between Groups	953.665	.000

Table 50. Games-Howell post hoc analysis for pairwise comparisons of Vickers microhardness between file types.

		Mean Difference	p	95% CI for Difference	
				Lower	Upper
Protaper Next	Hyflex CM	109.1	0.000	101.3	116.8
	EdgeFile	7.1	0.116	-1.2	15.4
	XP endoShaper	38.8	0.000	30.8	46.8
Hyflex CM	EdgeFile	-101.9	0.000	-108.0	-95.9
	XP endoShaper	-70.2	0.000	-75.8	-64.7
EdgeFile	XP endoShaper	31.7	0.000	25.2	38.2

5. DISCUSSIONS:

The knowledge of the mechanical behavior of endodontic instruments is very essential for clinicians to expect clinical performance, but the manufacturers do not make this information available(200). The present study was planned to compare the resistance to cyclic fatigue, bending (flexibility), and microhardness of endodontic instruments in order to evaluate their mechanical behavior in terms of improving predictable clinical endodontic outcomes. Evaluation of the mechanical properties of new NiTi rotary instruments and their impact on instrument performance is mandatory for clinicians in order to pick the best system for each case and improve clinical endodontic results(88). The results of our study lead to the rejection of the null hypothesis, as there were significant differences in the mechanical properties between the tested systems.

Fracture of the NiTi instrument is a major concern during canal instrumentation. Although multiple factors contribute to file fracture, cyclic fatigue has been shown as one of the leading causes when rotary files are used in curved canals(95,201,202). Consequently, The advancement in NiTi technology and manufacturing processes has led to a new generation of NiTi instruments, with better flexibility and more resistance to cyclic fatigue(187).

Most laboratory testing of NiTi rotary instrument fatigue performance has the drawback of being unable to account for the confounding effects of various parameters, such as material quality, design, and instrument dimensions, that are unique to the brand(s) under consideration. This makes determining the impact of a single variable on fatigue behaviors difficult(203). The clinical applicability of the results of such tests is difficult to assess because this condition differs from intracanal instrumentation in which the fracture occurs because of several factors (including torsional stress) that act together at the same time(176).

The cyclic fatigue test of the present study was performed by using a stainless steel block containing a single and a double curvature artificial canals for the sake of better standardization of experimental conditions and minimizes the influence of other variables not related to the instrument itself which was in accordance with a previously reported studies(147,176,194). Although the use of natural extracted teeth is the best specimen to evaluate the CFR of NiTi files in simulates clinical situations, they are very difficult to standardize(204). The use of simulated canals is particularly important when investigating challenging canals such as S-shaped canals because it is nearly impossible to select an adequate sample of anatomically standardized human teeth all with S-shaped canals and with similar canal lengths, degrees, and radius of both curvatures, diameters, also the natural teeth will undergone changes in the canal space during filling and make a problematic difference in results(147,176,194). Therefore, extracted teeth are not ideal for testing the cyclic fatigue of NiTi instruments. However, the results of studies that use artificial canals must be extrapolated to clinical conditions with care because of the difference between a stainless steel block and dentin(205).

The test models for cyclic fatigue measurement can be static or dynamic in nature. In static cyclic fatigue tests, the instrument is inserted into the simulated root canal to a definite depth and rotated without auxiliary movement until file fracture occurs(206). The static model produces the highest flexural stress at the center of the curve. In dynamic cyclic fatigue tests, the file is moved with pecking motion(axial) inside the simulated root canal with a certain amplitude to simulate the clinical situation(206). The dynamic movement of the file better simulates the stress that is generated on a file in a clinical situation as the maximum point of flexure varies along with the file throughout the testing procedure. In dynamic test designs, NiTi instruments have a longer lifespan and provide more clinically useful information than static tests(206). In the present study, the tests of instruments were done in the static cyclic fatigue test models and the reasons for that may be explained by the difficulty of standardization of the axial movement of the file without any lateral movement inducing torsional loads in a state of dynamic test models(206). Indeed, torsional and cyclic fatigue instrument fractures cannot be distinguished in dynamic test designs(206). Regardless of this fact which agreements with our study, even

if the simulated canal does not duplicate in vivo situations, it allows for the comparative testing of different instruments in a standardized environment(207). This was validated by the fact that all of the instruments tested practically fractured at the same point and can be accountable for better information on the impact of various design features of instruments or pre-treatment (heat or surface treatment) of the alloys on cyclic fatigue which effectiveness be more interesting for the improvement and optimization of new root canal instruments(207). The authors predicted that lateral pressure increases tensile strength, changing fatigue behavior, but further study is needed to determine the clinical significance of lateral pressure presence and magnitude on cyclic fatigue resistance. However, it can take risks that dynamic testing seems to be even more prone to inherent procedural errors compared to static set-ups. Presumably, variabilities in the amplitude of the axial motion of the instruments and the angle of instrument insertion displayed a significant impact on the obtained results(206). Li *et al*, 2002(110) presented that increasing the axial pecking motion of the instrument from 1 to 3 mm resulted in an increase in the time until fracture of about 15%. Nevertheless, it has been criticized that in a dynamic test model, it is difficult to keep the instruments in a precise trajectory(110,157,208). Furthermore, if the instrument was not fit retained in a precise trajectory at the simulated canal entrance, different bending properties and geometric features of the instruments may result in a different trajectory inside the curvature(183).

Thermomechanical machinery has a durable impact on their transformation behavior of NiTi alloys that's why it's frequently used for improving the microstructure and the performance of instruments during root canal shaping containing the cyclic fatigue resistance(90). In our study, EdgeFile and XP-endoShaper files presented greater cyclic fatigue resistance than HCM and PTN files. Keskin *et al* assessed the CFR of XP Endoshaper, K3XF, and ProTaper Gold F3 instruments at 35⁰C with a 60⁰ angle of curvature and a 5mm radius of curvature(155). Elnaghy and Elsaka compared the CFR of XP-endoShaper, TRUShape, Hyflex CM, iRace, and Vortex Blue instruments at 37⁰ C with 60⁰ angles of curvature and a 3mm radius of curvature(91). Silva *et al* studied the CFR of XP-endoShaper and the TRUShape instruments at 37⁰ C with 60⁰ angles of curvature and a 5mm radius of curvature(92). All the previous studies showed that XPS

instruments had greater resistance to cyclic fatigue, in agreement with the results of our study, it has been shown that the NCF values of XP-endoShaper were greater than HCM and PTN instruments at all groups. Also, it exhibited the NCF values of XP-endoShaper was greater than EdgeFile instruments at double canal curvatures in group 2, with similar values of NCF of both XP-endoShaper and EdgeFile instruments at double canal curvatures in group 1,3, and 4. Besides that, the NCF values of EdgeFiles were greater than all the instruments at single canal curvatures in all groups tested. However, so far there are no studies in literature comparing the cyclic fatigue of XPS with that EdgeFile instruments that's why we cannot compare our findings with other studies. These results might be attributed to the metallurgy of XPS as it is manufactured from MaxWire alloy. It is claimed by the manufacturer that MaxWire alloy delivers XPS instruments with great flexibility, superelasticity, and more resistance to fatigue(8). The shape memory of XPS allows it to take a predefined shape inside the canal(8). In our study, the NCF values of PTN was the lowest compared to other instruments at both angles except in groups 2,3, and 4 there were similar values of NCF in both PTN and HCM at double canal curvatures, in agreement with a previous study that reported a Protaper Next (M-Wire file) revealed the lowest NCF values compared with Hyflex CM, EdgeFile, and OneCurve files at both room and intracanal temperature(170). Also, in another study, Elnaghy *et al* compare the cyclic fatigue resistance of Protaper Next files with Twisted Files, Hyflex CM, and Protaper Universal at room temperature and they reported that the twisted files had the greatest NCF values with no statistically significant CFR in both PTN and HCM(141). The explanation of these contradictory findings may be related to that the files constructed from CM wire alloys have a significantly improved CFR compared with M-Wire and conventional NiTi files. In CM wire alloys there is the greatest proportion of the amount of the martensite phase and low austenite phase which is more flexible with an improved CFR in compared with M-Wire alloys that have the greatest proportion of austenitic phase and low martensite phase because the nature of the martensite content of instruments made of CM alloys has a positive effect on their cyclic fatigue resistance(52). Moreover, cross-section design and material property appear to be detrimental to the torsional behavior and stress-induced by NiTi rotary endodontic instruments under tension or twisting(145,203,209). The instruments with a large cross-sectional configuration area could have greater torsional resistance and low cyclic fatigue resistance(92,203,209).

Consistent with our study, the lowest values of NCF of PTN also may be related to the PTN instruments having a rectangular cross-sectional design. However the HCM Files has a symmetrical triangular cross-sectional design, while EdgeFile has a modified convex triangular cross-section, and XP-endoShaper has a triangular cross-section with small core diameter(8,91,92,155,170,203). Cheung *et al* revealed that a triangular cross-sectional configuration had a higher cyclic resistance than a square cross-sectional configuration using a finite elemental analysis(203). This difference may be related to the reduced metal mass of the instruments with a triangular cross-section design(145). Zhang *et al* demonstrated that the cross-sectional design had a greater impact than taper or size of the instrument on the stresses developed in the instrument under either torsion or bending(209). The authors explained that in which the dimensions (tip size or taper) of the instruments seem to behave a little effect on the maximum von Mises stress when the instrument was bent to a similar angle (e.g, 30 degrees) of curvature; only a small effect on the maximum reaction stresses might be noticed(209).

In the present study, we used different rotational speed settings according to the manufacturers' recommendations (varying from 300 to 800) for each instrument which similar is to previous studies, and we compared the cyclic fatigue behavior of the instruments using NCF scores to standardize the variations introduced by the different speeds under which instruments were operated(91,141,147,170). Lopes *et al* presented nearly a 30% reduction in the detected number of cycles to fracture as rotational speed was increased from 300 to 600 RPM (100% increase in speed)(210). However, some authors reflect that the rotational speed was not a significant factor concerning instrument fracture, others consider it to be critical(211). The life expectancy of a file was related to a specific number of rotary cycles. Therefore, a slower rotational speed would mean that the clinical life span is prolonged, breaking only occurred after reaching a specific number of rotations known as "maximum angular deflection"(118). Clinically, the fatigue of an instrument may be related to the degree of flexure when placed in a curved root canal especially when these curves are more prominent, the instrument submits to greater cyclical fatigue, and thus its life expectancy is lower(20,211). Pruett *et al* stated that cycles to failure were not affected by speed on the conditions of artificial metal canals

and it may be specified that the curvature of the canal is a factor that is much more important than rotational speed when it comes to the fracture of instruments(20). Consistent with our study, the fracture of the all the instruments was occurred first in the accentuated curvatures at apical portion of the canal in spite of the speed use. The explanation for that might be by the fact that curvature with a small radius usually occurs in the apical foramen, and thus it is more possible that breakage would take place toward the tip of the file(20). Making an allowance for the different rotation speeds between the instruments, one may reason that the heat energy produced may be different and this might lead to a temporary increase of temperature, which may have some influence on the results. Pedulla *et al* evaluated the effect of rotational speed on cyclic fatigue of Mtwo (VDW) instruments and presented that speed did not affect the fatigue life of these instruments(212). Nevertheless, the XP-endoShaper was energetic with higher rotation speed and still exhibited better cyclic fatigue results when compared with PTN and Hyflex CM files which similar to the earliest studies(91,154). Therefore, the rotational speed rate at which NiTi rotary instruments should be driven is a variable that remains to be clarified, an unresolved and controversial issue. Preferably they must be used at a rate that minimizes the incidence of the fracture and deformation while improving efficiency at the same time(213).

In the present study, both simulated root canals were used milling with trajectory or conical in the shape with wider at the coronal and narrower at the apical portion, one of them had a single angle of curvature 90° with 5mm radius, which represents the complicated clinical situation, the instruments fractured about 5mm from the tip which corresponds to the mid-point of the curvature, the maximum flexure of the shaft, and it indicated precise positioning of the instruments. Other simulated root canals were used in our study with a double canal curvatures “ S-Shape”, one of them located at the apical portion with an angle of curvature of 60° with a 2mm radius and other curvature located at the coronal curve angle of curvature of 45° with a 5mm radius. With the exception of PTN files, all instruments tested in the present study were first fractured in the area of apical curvature with statistical significance. The possible explanation for this result may be that the apical curvature was more abrupt or severe (a radius of 2mm) than the coronal

curvature had a 5mm radius. Also the number of cycles to fracture being statistically lower in double-curved canals when compared with single-curved canals. The design of our simulated canal device and the finding were in agreement with the previously reported studies evaluating cyclic fatigue resistance of various files(20,194,214). Plotino *et al* stated that the trajectory of the files inside the tubes has highly significant impact on the outcome of studies(182). In a critical review of cyclic fatigue testing methods, Plotino *et al*(176), hypothesized that although many studies at that time (and still today) used a roughly comparable design, no attention had been paid to the diameter of the tubes or the fit of the instrument inside the tubes. Nevertheless, when looking at the details of the published studies a large variance in details of study protocols becomes evident, making comparisons of results very difficult, problematic, and to some degree even impossible. Furthermore, studies that used just single-curved tubes were considered as studies that used double-curved tubes (S-shaped) to create a new parameter, making meaningful comparisons practically impossible(176). The static model as used by Pedulla *et al*(149) and others(141,176) generates the highest flexural stress at the center of the curve. Lopes *et al* investigated the effect of the position of the curvatures along the simulated root canal on the resistance to cyclic fatigue, and it was discovered that a curvature in the middle of the canal with a straight line at the end of the curvature reduced the number of fractures when compared to a curvature at the apical end with no straight portion at the terminal end of the curve(215). Also, when increased the angle of curvature and reducing the radius arc length results in a reduced lifespan of NiTi instruments(148). Besides, it was recognized that the extent of the curvature in the area of procedure was one of the primary variables that contribute to instrument fatigue fracture. Under the clinical conditions, two curves can be present in the same root canal trajectory. This form of geometry is referred to as "S"-shaped, and it is one of the most challenging clinical situations in which to use NiTi instruments(20). An additional challenge is that in many cases, double curvatures are not visible in conventional radiographs. Al-Sudani *et al*(194) stated that fatigue of NiTi instruments when used in S-shaped canals, occurs very quickly and that meaning instrument fractures might occur after a very short time of use inside the apical curvatures. It has been shown that S-shaped canals influence the CFR of NiTi files, with the number of cycles to fracture being statistically lower in double-curved canals when compared with single-curved canals and the explanation for that double curvature canals represent

much more stressful and challenging anatomy than single curvature canals(216). Furthermore, despite there was a drop of NCF of PTN in our study from single to double canal curvature, and from coronal curve to apical curve, no statistical significant difference was observed. Despite the use of less speed and torque, it fractured within seconds immediately after its operation, directly without any resistance to fatigue failure, and this was interpreted as it could not withstand the high stress in severely challenging canals, regardless of their shape and location, and it could also be related to PTN's large taper and low flexibility when compared to other instruments tested.

A metal canal space is filled with a lubricant like synthetic oil or other solutions to reduce the friction of the file, thus preventing torsional load. Contradictory results on the cyclic fatigue resistance of NiTi instruments after contact with NaOCl solution with different tests and immersion techniques have been reported. Therefore, to a certain extent, the use of different lubricants during testing may be responsible for the unpredictable results(217). The results of our study showed the fracture of EdgeFile and XP-endoShaper occurred with higher NCF values in dry condition compared to NaOCl (moist condition) which was reported in the previous study on different experimental instruments(217). Up to this moment, no study has evaluated the effect of immersion in NaOCl in the cyclic fatigue resistance of EdgeFiles, and that's why the results of our study on EdgeFiles cannot be directly compared with other studies in the literature. Hacer Akse *et al* showed the NaOCl immersion reduced the cyclic fatigue resistance of XP-endoShaper, and the explanation for that may be related to the NaOCl might cause microstructural defects on MaxWire alloy leading to more stress concentration and decrease the CFR of XP-endoShaper due to the smaller taper size and core diameter of the instrument(161). Elnaghy & Elsaka *et al* demonstrated the fracture occurred in Reciproc instruments after 1251 cycles, 882 cycles in air, and NaOCl, respectively (this difference was nearly 250%), and they conclude that the fatigue resistance for instruments tested in the air was higher than in saline and NaOCl solutions(217). Furthermore, the immersion of the instruments in the water at simulated body temperature was associated with a significant drop in the cyclic fatigue resistance of the instruments(146). Also, it has been reported that water has a more detrimental impact on the fatigue resistance of

the NiTi instruments than air, since water seems to have some influence on the crack initiation mode in the material(146,217). However, in vitro fatigue testing offers a simplistic equivalent to the clinical condition. Therefore, the cyclic fatigue test would be accepted at 37⁰ C to simulate patient body temperature(146). Besides from that, irrigation solutions in the intracanal were measured at body temperature starting 30 seconds after the irrigant was delivered(146,218). Pedullà *et al* reported that static or dynamic immersion in NaOCl for 1 minute or 5 minutes did not reduce the cyclic fatigue resistance of NiTi instruments significantly(65). Cai JJ *et al* investigate the effect of irrigation on the surface roughness and fatigue resistance of HyFlex and M3 controlled memory (CM) wire NiTi instruments and they revealed a rotary dynamic immersion in 17% EDTA and 5.25% NaOCl solutions for 10 min did not significantly decrease the cyclic fatigue resistance of CM NiTi instruments(151). Pedullà *et al* evaluate the effects of NaOCl immersion and sterilization on the cyclic fatigue resistance of heat-treated NiTi rotary instruments (HCM and Twisted files), they founded immersion in NaOCl did not reduce significantly the cyclic fatigue resistance of all heat-treated NiTi files tested(156). The different post-machining thermomechanical treatments that the NiTi alloy is subjected to during the manufacturing of Hyflex CM could explain these results(156). Paulo Jorge Palma *et al* evaluated the effect of immersion in 3% NaOCl solution on the resistance to cyclic fatigue of three NiTi rotary file systems, Protaper Next (PTN), Hyflex CM (CM), and Hyflex EDM (EDM), they showed that the immersion in NaOCl decreased the resistance to cyclic fatigue of all tested instruments but affected more those manufactured from CM wire(163), and this is following the result of the previous study which showed that files constructed from M-Wire alloys present a higher resistance to sodium hypochlorite action(219). In our study, although there was a decrease in the NCF values of PTN and Hyflex CM files from dry to humid (NaOCl) conditions, it was not statistically significant. The explanation for these findings maybe because of the type of analysis. The cyclic fatigue device generated the most stress in the center of the simulated curve, so if a corrosive zone exists at that level, the instrument may fracture prematurely. However, if the corrosive event occurs in a location other than the area of highest stress created by the testing device, the instrument's resistance to cyclic fatigue may not be diminished(65). The actual influence of NaOCl on the NCF values still unclear. The corrosive abilities of 5% NaOCl during the rotating(flexing) state of files may be related

to increased the growth rate of cracks and reduced NCF values. This phenomenon is known as stress corrosion cracking (SCC) in which normally ductile materials, particularly alloys, are expected to fail unexpectedly due to the rapid growth of the crack when the material is subjected to tensile stress in a corrosive medium (chlorine-containing media). SCC has also been reported to increase at elevated temperatures, which in our study was at body temperature 37⁰ C (220). In another study, the immersion of instruments in the NaOCl solution created a statistically significant reduction in the mean number of cycles, regardless of the duration(163). This localized corrosion attacks have been identified as preferred sites for the formation and propagation of critical cracks, resulting in a considerable reduction in the instrument's typical life(221). Furthermore, these contradictory results might be connected to how NaOCl was immersed; in our study, we investigated the impact when the files were exposed to the corrosive environment in a flexing and rotating state during the cyclic fatigue test, which was not consistent with other previous experiments studies(65,221,222).

The temperature has been stated as another important confounding factor in cyclic fatigue studies. Numerous studies have shown that the temperature of the environment has a significant impact on the cyclic fatigue behavior of NiTi instruments(130,146,158,165,170,223). The metallurgy of NiTi alloys reveals an extremely different behavior at room or body temperature(52). Our findings demonstrated a significant drop in NCF resistance values in EdgeFiles and XP-endoShaper files at body temperature compared to room temperature, but no statistically significant impact in PTN and HCM files, despite a reduction in NCF values in group 2 compared to group 1. In agreement with our study, Dosanjh *et al* examined the effect of different temperatures on the cyclic fatigue of three NiTi rotary files (EdgeFile, Vortex Blue, and ESX) at 3⁰ C, 22⁰ C, 37⁰ C, and 60⁰ C, and they stated that the temperature was found to significantly affect the cyclic fatigue of NiTi rotary files. They reported that the NCF values of EdgeFiles increased when temperature increased from 3⁰ to 22⁰C, and decreased significantly when it increased from 22⁰ to 37⁰ C(130). The explanation of the highest NCF values of EdgeFiles is attributed to that the EdgeFile is predominantly in a martensitic phase at room temperature, which is responsible for their lack of shape memory. Additional

cooling of the EdgeFile to 3⁰ C resulted in a decrease in NCF. This reduction in NCF might be due to a same mechanism that causes conventional metals to become more brittle as they cool, causing them to fracture. The change to an austenitic phase, which reduced the NCF, was most likely produced by heating(130). Furthermore, our findings demonstrated that the NCF values of both the EdgeFile and the XP endoShaper in double canal curvature at room temperature were similar, with no statistically significant differences. The NCF values of XP endoShaper were greater than EdgeFiles at body temperature, while the NCF values of EdgeFiles were similar to HCM files. We can't compare our findings to any other study because there was none in the literature comparing the effect of temperatures on EdgeFile and XP-endoShapers together. However, these results may be related to the fact that both files with more the martensite phase in a low-temperature environment have same behavior in more challenging canals as S-shaped canal at room temperature. The fact that EdgeFiles were affected worse by body temperature than XP-endoShaper files may be the reason why EdgeFile's NCF values were much lower in double canal curvatures in compared to XP-endoShaper files. In another study, H. S. Topcuoglu *et al* compare the resistance to cyclic fatigue of ProTaper Next X2, Hyflex CM, OneShape, and ProTaper Universal F2 NiTi files in an artificial root canal with a double (S-shaped) at room temperature and they reported the CFR of the PTN X2 and HCM instruments was significantly higher than the OS and PTU F2 instruments in the apical curvature. There was no statistical difference in the cyclic fatigue resistance of the PTN X2 and HCM instruments in the apical curvature, besides, there was no statistical difference between the OS and PTU F2 instruments in the apical curvature, and PTN X2, OS, HCM, and PTU F2 instruments presented similar CFR values at the coronal curvature(147). This is in contrast to our findings, which showed that HCM had higher NCF values than PTN at single canal curvatures at both temperatures and double canal curvatures at room temperature, with the reasons being that ProTaper Next (M-Wire file) had the lowest NCF values compared to other files, and CM Wire files had a significantly improved CFR compared to other files. CM files are more flexible and have a higher CFR than austenitic files in M-Wire files because they include the most martensite phase(52). Our findings revealed that at body temperature, the NCF values of PTN and HCM were similar at the apical curve of double canal curvatures, which was consistent with previous study(147). This might be because HCM files alloy's NCF value

is considerably more impacted by body temperature than PTN, and PTN has the same behavior in CFR regardless of temperature, meaning that PTN did not exhibit any resist to CFR in greater stress difficult canals. H. S. Topcuoglu *et al* compared the cyclic fatigue resistance (CFR) of three controlled memory (CM) NiTi rotary files (One Curve, EdgeFile and HyFlex CM) in comparison with a file (ProTaper Next) made from M-wire NiTi alloy at two different temperatures (room and intracanal) in an S-shaped canal and they reported that testing at body temperature led to a significant drop in CFR of all tested files compared with testing at room temperature. They also reported that the PTN had the lowest NCF values at both temperatures, whilst at body temperature, the EdgeFiles showed highest the NCF values compared to other instruments, and that the NCF of three controlled memory files had similar values at room temperature(170). The conflicting results between the previous study itself and our study may be due to variations in experimental design and test pattern, as well as the impact of the cross-sectional area, metal mass, size, and taper of tested files on these results. Vasconcelos *et al* compared the fatigue resistance of four different NiTi (Universal ProTaper F2, HyFlex CM, TRUShape, and Vortex Blue) at 20⁰ C and 37⁰ C, and they showed the NCF values was significantly higher at 20⁰ C compared with at 37⁰C, with differences ranging from 33%–85% respectively for all the instruments(146). RM Cardoso *et al* investigate the influence of temperatures of 20⁰ C and 37⁰ C on the CFR of XP Endoshaper, ProDesign logic, and iRaCe and they revealed CFR was significantly reduced at 37⁰ C body temperatures compared to 20⁰ C room temperature (165). The reasons for that may be related to the influence of temperature on the behavior of the MaxWire surface treatment of the XP-endoShaper files. Because the experiments were carried at at body temperature, it shifts to its austenitic phase at higher temperatures, such as 37⁰ C. These properties of the XP-endo Shaper may have negatively impacted the cycle fatigue resistance(165). Elnaghy *et al* compared the cyclic fatigue resistance of the XP-endoShaper instruments with TRUShape, HyFlex CM, Vortex Blue, and iRace NiTi rotary instruments at body temperature(91). They conclude that XP-endoShaper instruments revealed the highest cyclic fatigue resistance compared to other instruments, consistent with the results of the present study, which showed the NCF values of XP-endoShaper higher than PTN and Hyflex CM files at both temperatures. The explanation for that may be related to changing the taper of XP-endoShaper, the initial small ISO diameter with a narrow taper

make the instrument more resistant to cyclic fatigue. The XP-endoShaper instruments had unique properties from superelasticity and shape memory because of these innovative MaxWire NiTi alloy of the XP-endoShaper instrument, and these instruments can behave according to the temperature(91). Similar results to Silva *et al*(92), and Keskin *et al*(155). Plotino *et al* evaluate the cyclic fatigue resistance of ProTaper Universal and ProTaper Gold NiTi rotary files at room and intracanal temperatures and they showed intracanal temperature influenced the cyclic fatigue resistance of instruments produced with traditional NiTi, whereas it did not influence the fatigue life of instruments produced with gold heat treatment(223). Adiguzel *et al* assessed the cyclic fatigue resistance of XP-endoShaper, HyFlex CM, FlexMaster, and Race instruments at body temperature(154). The results showed that XP-endoShaper highest one compared to others. Thus, in addition to the previous author's explanation, it may be attributed to the metallurgical differences among the instruments. XP-endoShaper and HyFlex CM instruments were produced from heat-treated alloys, whereas FlexMaster and Race instruments were produced from conventional NiTi alloys(91). The austenitic finishes (A_f) temperature of Hyflex CM was about 47°C or closed to that range, indicating that the specific peak shape for Hyflex CM suggests that the conversion is not fully finished at body temperature and will have a mixed martensitic, R-phase, and austenitic structure at body temperature but that a significant proportion is already austenitic(51,146). These features of HyFlex CM instruments might have positively affected the cyclic fatigue resistance because the experiments were carried out at body temperature. The transition of the XP-endoShaper instrument from the martensite phase to the austenite phase takes place at body temperature between 32°C and 37°C with an A_f temperature around 35°C , this transition might have negatively affected the cyclic fatigue resistance(8,165,224). Yılmaz *et al* compare the cyclic fatigue resistance of HyFlex CM, Typhoon CM, and EdgeFile X3 NiTi files with a Controlled Memory alloy under a static model at room temperatures and they revealed there was not any statistical difference in term of NCF between all the instruments(150). These findings, according to the scientists, may be related to the behavior transformation of alloys at different temperatures. At room temperature, CM alloys exist in both austenite and martensite phase, because martensite is softer than austenite, and the higher martensite content of files made of CM alloy has a positive effect on their cyclic fatigue resistance(103,150,224,225). Shen *et al* assess the effect of

different temperatures (0⁰ C, 10⁰ C, 22⁰ C, 37⁰ C, and 60⁰ C) on the cyclic fatigue life of nickel-titanium (NiTi) file using three superelastic NiTi files (EndoSequence, ProFile, and K3), and 3 heat-treated (K3XF, Vortex, and HyFlex CM) NiTi file(158). The result exhibited that the cooling down to low temperatures may be a remarkable plan to improve the fatigue resistance of the rotary NiTi file. The author's explaining that result may be related to proprietary heat treatments that increase the so-called austenite start (As) and austenite finish (Af) temperatures, which designates temperatures to induce the transformation of the metallic structure from martensite to austenite starts and is completed. When the temperatures are between As and Af, the alloy consists of austenite and martensite, which has higher fatigue resistance(45,158,224). Besides that, when the alloy cools down to a temperature close to As, the percentage of the martensitic phase might reach the maximum range probable for the alloy itself(158). It could partly explain why no difference in the NCF was found on HyFlex CM at 0⁰ C, 10⁰ C, and 22⁰ C because the As of HyFlex CM is around or more than 21⁰C(51,71), The Af of CM Wire instruments was above intracanal temperature (around 47–55⁰C)(51). At body temperature, the cyclic fatigue resistance was found to be decreased mostly for all instruments. To explain the significant reduction in fatigue life, one may consider the pertinent transformation temperatures. DSC was used to investigate the phase transformation of NiTi endodontic instruments. In this analysis, certain peaks related to cooling and heating cycles indicate the martensitic (cooling) and austenitic (heating) transformations(33,226). The constant temperature was kept in each group during the experimental process to minimize the effect of confounding factors.

The selection to reuse NiTi files for more than one patient (many uses) makes instruments sterilization a must in every health-care environment, as well as a process to avoid cross-infections(227). Sterilization of rotary NiTi files requisite before use(except for pre-sterilized files), and this is repeated if the files are reused or carried forward between appointments of the same patient(121). The literature focused on the impact of sterilization on the NiTi instruments showed contradictory results(121). Numerous studies had evaluated the effects of sterilization on the mechanical properties of files manufactured with the conventional NiTi alloy occasionally showed differing

results(116,228). Although some researches claim that autoclave sterilization has no effect on the fatigue resistance of NiTi files(116,195,229), others have discovered that when subjected to both dry heat and autoclave sterilization, average NCF values are higher(195,228) or lower level(229). Thus, in the present study, we investigated the effect of both NaOCl contact and autoclave sterilization on the cyclic fatigue resistance of 4 heat-treated NiTi files. To prevent instrument exposure to the uncontrolled stresses of routine clinical situations, the current study used rotary endodontic instruments that had not been used clinically (a new one) as in previous reports(228). The protocol of this study includes dynamic immersion of all evaluated instruments in a 5% NaOCl solution at 37⁰ C during the cycle fatigue test to get closer to clinical conditions(91,156). However, most studies did not simulate the clinical situation. The findings of this study revealed that sterilization had a positive impact on EdgeFiles, with improved NCF values in groups 3 and 4 compared to NCF values in group 2. However, sterilization had a negative impact on XP-endoShaper files, with NCF values reduced in groups 3 and 4 compared to group 2. There was no statistically significant effect of sterilization on CFR of PTN and Hyflex CM, despite an improvement in CFR of PTN and Hyflex CM. Also, there was no statistical difference between one or five cycles of sterilization. According to our research, there has never been a study in the literature that evaluated the effect of sterilization on EdgeFiles and XP-endoShaper, therefore our findings cannot be compared to those of other studies. Pedullà *et al* they investigated the effects of NaOCl immersion and sterilization on the cyclic fatigue resistance of heat-treated NiTi rotary instruments (HCM and Twisted files), and discovered that repeated sterilization cycles had no effect on the cyclic fatigue of HCM NiTi files, with the exception of TFs, which showed a significant reduction in flexural resistance after 3 sterilization cycles(156). These findings are consistent with our research, and the reason for this could be that the NiTi alloy was subjected to various post-machining thermomechanical treatments during the manufacturing of Hyflex CM(156). Zhao *et al* they compared the cyclic fatigue resistance of Hyflex CM, Twisted Files, K3XF, Race, and K3, as well as the effect of autoclave sterilization on the CFR of these instruments both before and after cycle, and found that autoclave sterilization significantly increased the mean of the cycle of fracture (MCF) of Hyflex CM and K3XF ($p < 0.05$) both before and after the files were cycled(121). This contradicts the findings of our investigation, which showed no effect of sterilization on

the CFR of Hyflex CM. The different finding between our study and that of Zhao *et al*(121), may be explained by different instrument sizes, cycles of sterilization condition; 1or 5 cycles of our study and 10 cycles of Zhao *et al*(121), and fatigue test angles; 90° and a 5mm curvature radius and S-shape curvatures of our study vs. 60° and a 3mm curvature radius of Zhao *et al*(121). In other studies, they reported that sterilization at temperatures below 170° C did not provide enough energy for the heat treatment effect to allow changes in the crystalline phase. The temperature of 170° C is requisite to start reordering, 430° C–440° C to achieve maximum fatigue resistance, and 640° C is requisite for complete martensitic to austenitic conversion(121,229,230). Plotino *et al* stated that repeated cycles (10 cycles) of autoclave sterilization (134° C for 35 min) did not influence the mechanical properties of K3, Mtwo , and Vortex NiTi instruments(195). These findings are consistent with those of Hilfer *et al*, who found that the mechanical properties of instruments made with the new M-Wire NiTi alloy (GTX and Vortex) were not affected by heat autoclave sterilization, as they were for instruments made with traditional NiTi alloy (K3 and Mtwo)(229). These findings are also in accordance with the results of our study which showed that the PTN made from M-wire NiTi alloy was not affected by autoclave sterilization. In addition, on the contrary with our results, Özyürek T *et al* compare the cyclic fatigue resistance of ProTaper Universal (PTU), ProTaper Next (PTN), and ProTaper Gold (PTG) and evaluate the effects of autoclave sterilization on the cyclic fatigue resistance of NiTi instruments. They reported autoclaving increased the cyclic fatigue resistance of PTN and PTG, and the authors explained the reasons for that those NiTi alloys subjected to heat treatment during the manufacturing process(153). The difference between our findings and theirs might be due to differences in research protocol design (angle of curvatures, sterilization protocol, and temperature). Thus, the impact of multiple usages of endodontic files should be considered. Nevertheless, the UK Chief Dental Officer has recommended single use of endodontic files(231). Besides that, the instruments were submitted to standardized fatigue testing in the current study. In the clinical situation, the instrument may be subjected to many repeated variables at the same time as reverse torsional loads and cyclic fatigue stresses inside the canal(121).

The three-way analysis of variance (ANOVA) employed in our study allowed us to evaluate the interaction effect of three predictor factors (the file types, angle and

location of canal curvatures, and medium conditions as temperature, NaOCl immersion, and sterilization) to the cyclic fatigue failure. All three predictors were significant interactions and associated with file fatigue. The strongest predictor was the file type (PTN was worse than other experimental files), followed by angle and location of canal curvatures (Double worse than a single canal, and apical curve worse than coronal curve), and medium conditions (body temperature worse than room temperature, NaOCl immersion adversely impact on CFR of XP-endoShaper and EdgeFiles, Sterilization had a positive impact on EdgeFile and negative impact on XP Endoshaper with no difference of benefits of the number of cycles of sterilization 1 or 5 cycles).

One of the limitations of this study was the different tapers used for the instruments tested. PTN X3 instrument was selected because of its continuous rotary motion systems rotate eccentrically or asymmetrically inside root canals resemble XP-endoShaper files which had the design of snake shape performs an asymmetric rotary motion ‘swaggering motion’ by taking on a semicircular shape when it expands at a temperature of 35⁰ C or higher(232,233). The other tested instruments were selected because their taper is 0.04 and it was claimed by the XPS manufacturer that the preparation of the canal starts with 0.01 taper and expands inside the canal to achieve at least a taper of 0.04 at body temperature(8). The taper is one of the factors affecting the mechanical properties of NiTi files because the file diameter is inversely proportional to cyclic fatigue resistance. Lower-tapered files ensure fewer file fractures and a more conservatively shaped canal(234). Furthermore, other studies in the literature have compared the cyclic fatigue resistance of files with different tapers; some of those studies reported that higher or similar cyclic fatigue resistance values can occur in instruments with a larger taper in comparison to instruments with a smaller taper, and the explanation of the reasons for that the cyclic fatigue of instruments did not only depend on the taper but also cross-section design, manufacturing alloys, and other factors(152,203). Besides from that, the major purpose of this experiment is to compare the performance of various file systems in terms of cyclic fatigue resistance. The findings of the current laboratory investigation are intended to disclose the behavior of the instruments that were examined. However, more in vivo research is needed to confirm the current study's findings.

The instruments were fractured at the point where the most flexure was accumulated, which corresponded to the curvature's midpoint. Our findings are consistent with those of previous research(20,141). There was no significant difference in the mean length of the broken fragments of all experimental instruments in the same curvature, but only at various canal curvatures was there a significant variation in fracture length (FL). The FL at double canal curvatures was 3.1mm, whereas the FL at single canal curvatures was 5.1mm. Furthermore, the FL at the apical curve was 3.1mm, whereas the FL at the coronal curve was 5.7mm. The fractured fragment of the file was at the center of the curvature or just below this point, which confirms the positioning of the files in a precise trajectory, and also the difference of FL at different canal curvatures attributed to the location of angles and radius length. All the fractures revealing a narrow area of maximum flexure across file groups(20,141). Besides that, the separation of unbound instruments in the region of the most severe canal curvature would be considered a result of cyclic fatigue with any instrument system(20). Fractured instruments showing a ductile fracture was occurred due to the accumulation of metal fatigue(235). Furthermore, the length, type, and position of separating endodontic instruments affecting the removal procedures for them from challenging curved root canals in clinical manners(236). The removal of NiTi instruments is more difficult than the removal of stainless steel instruments. The reason for this is that NiTi instruments frequently separate at a shorter fragment length in the curvature of narrow root canals, with the rotating action locking them into the dentin(237). Moreover, damage from ultrasonic vibration during the effort to remove the fragment might cause the NiTi instruments to split or shorten further. Additionally, the shape memory of NiTi alloy raises the difficulty level because, once released from the dentin, they tend to straighten and re-engage with the root canal wall(238). So far, several techniques for instrument removal have been reported. However, none has been proven to be completely effective, and all have a significant rate of canal injury, such as perforation(239). Y Terauchi *et al* reveals that as the degree of curvature increases, a longer preparation time is required for separating instruments over 3.1 mm in length, but instruments under 3.1 mm can be reliably removed using ultrasonic instruments regardless of the degree of curvature. Instruments separated by more than 6.4 mm tend to be difficult to remove using ultrasonic instruments and should be recovered using a loop or the XPS instrument. The results of his study also show that when removing separating

instruments longer than 4.5 mm, a loop or XPS should be considered because more canal dentin can be saved(240). Moreover, the clinician may prefer to have the fracture occur closer to the apex than farther below the canal curve, as this will allow for better cleaning of the remaining root canal area and easier surgical care if necessary.

Scanning electron microscope interpretations of the fractured instruments revealed that the instruments existing with manufacturing grooves and disruption of the cutting edge. These deficiencies are known to be stress concentration points allowing crack initiation from these grooves/ at the cutting edges or propagation along with them(103,141,148,149). Fractographic features of scanning electron microscopy analysis showed similarly and the classical cyclic fatigue configuration of a somewhat smooth area of crack initiation from single or multiple crack origins and the presence of multiple crack locations are known to improve the cyclic fatigue life of a material because the applied stresses are divided between all the cracks, thus decreasing the strain localization and the speed of propagation of the fatigue(77,103). The fracture surfaces presented characteristics of the ductile type (the ability of the material to undergo plastic deformation before fracture); the fatigue striations (ripple appearance) was evident, fibrous dimple marks were observed(77,148,149), and formation of microvoids dispersed over the entire surface area within the metal because of the action of normal stresses inherent to cyclic fatigue(92). Nucleation growth and microvoid coalescence which ultimately weakens the metal result in a fracture(197). Moreover, in the present study, the area occupied by the crack growth region or dimple region was smaller and scattered in control groups than others. Hence, it is not surprising that instruments in control groups had superior fatigue resistance than the other files from other groups(103). Theoretically, the continued reduction in the clear area of the remaining intact portion due to the gradual propagation of a fatigue crack would reduce the part's load-bearing capability to the point where it breaks in the next load cycle due to simple overload. There was also a substantial relationship between strain amplitude and the area fraction occupied by the dimple region(77,241). Finally, the analysis of the views obtained with SEM from the surface instruments allows the superficial changes in the instruments exposed to sodium hypochlorite and other circumstances to be verified. Surface corrosion will most likely

appear as a darker hue on the broken XP-endoShaper surface than the rest of the surface of XP-endoShaper(163).

The flexibility of NiTi rotary instruments is an important property because it improves the mechanical behavior and performance of endodontic instruments when preparing curved canals(200). Besides, the endodontic instrument's flexibility has a substantial impact on the outcomes of both torsional and cyclic fatigue testing(100,187). The increased flexibility allows for a lower load on the instrument cutting blades in a curved canal, resulting in less stress on the instrument and a lower chance of breakage(200). In the present study, the instruments were fixed 3mm away from the tip because this is the point of worry for instruments submitted to bending according to ISO 363101-1 specification, and also the maximum curvature is found in the majority of root canals at this point(242). The finding of our results showed the flexibility of test brands from highest to lowest as follows: XP-endoShaper, EdgeFile, HCM, and PTN, respectively. There were a few published articles that assessed the bending resistance properties of numerous file systems. To this date, according to our knowledge of literature research, there were not any published articles for XP-endoShaper files. G. Pongione *et al* conclude whether this new manufacturing method produces NiTi instruments (Hyflex) of superior flexibility and/or superior's resistance to cyclic fatigue when compared with instruments produced by a traditional manufacturing process (Endosequence instruments) or thermally treated NiTi alloy (Vortex instruments: M-wire), they reported the CM-wire manufacturing process was capable of producing NiTi rotary instruments more flexible than conventional or M-Wire alloys(171). Elnaghy and Elsaka *et al* compare the mechanical properties of ProTaper Next files (PTN) with Twisted Files (TF) and RaCe (RC), they concluded that TF displayed more flexibility compared with PTN and RC files(173). The authors explained that the TF alloy has superelasticity and shape memory, which allows for the development of more flexible instruments when compared to NiTi instruments made by grinding(243). As a consequence, TF could be used for preparing curved canals, while PTN has shown more resistance to torsional stresses and could be used to prepare highly constricted root canals(173). Santos *et al* evaluate the flexibility and torsional stiffness of a controlled memory (CM) NiTi file and compare its mechanical reactions with those of a superelastic NiTi file with the same geometry using

finite element simulation, they confirmed the CM NiTi files had higher flexibility and potential fatigue resistance(172). Lopes HP *et al* evaluate the semiquantitative composition, flexibility, and microhardness of endodontic instruments with conventional (RaCe) and CM NiTi alloy (Hyflex CM,) and they conclude that Hyflex CM had higher flexibility(174). Goo *et al* compare the bending stiffness, cyclic fatigue, and torsional fracture resistances of heat-treated and conventional NiTi rotary instruments. V-Taper 2 (conventional alloy), V-Taper 2H (CM alloy), Hyflex CM (CM alloy), HyFlex EDM (CM alloy), and ProTaper Next X2 (M-wire alloy) were tested, the result of the study exhibited that CM-wire instruments displayed higher flexibility and cyclic fatigue resistance than M- wire and conventional NiTi instruments(175). Due to the transformation temperatures increase by the way the nickel content decreases, and therefore with the reduction of the nickel content in the NiTi alloy, the Af of CM alloy rises as well as the tendency to get stable martensite at the working temperature(172). Testarelli *et al* presented that NiTi alloy with a lower weight percent of nickel as in CM wire alloys has better flexibility than conventional NiTi alloy(244). Therefore, CM-wire instruments have less resistance to bending motion, and they are easy to bend in a curved canal and preserved the original root canal anatomy shape(175). All the previous study in agreement with the results of our study that showed HCM files manufactured from CM wire alloys more flexibility than PTN manufactured from M-Wire alloys. Chad Hansen *et al.*, in contrast to our findings, compared the torsion and bending properties of a brand new file system EdgeFile X7, EndoSequence, Vortex Blue, K3XF, and HyFlex CM, and determined that HyFlex CM had the maximum flexibility, followed by EF X7(138). The difference in results might be attributable to the bending device configuration, as well as the fact that the cyclic fatigue resistance of endodontic instruments was not taken into account in the previous study. Also, the findings of our research demonstrated that EdgeFiles have more flexibility than HCM files, which is supported up by the fact that EdgeFiles have higher NCF values than HCM files. Besides, Chad *et al.*, stated that of the files analyzed, the X7 had the best combination of strength and flexibility(138).

Hardness can be used to expect wear resistance and the ability of NiTi rotary endodontic instruments to cutting tooth structure. The surface hardness of the NiTi alloy is essential to extend the working life and wear resistance of NiTi instruments which

improving by surface engineering techniques(88,245–247). Besides, previous studies showed that the surface hardness of NiTi rotary instruments significantly contributes to their cutting ability and wear resistance during canal instrumentation(60,88). Accordingly, the previous study stated that the average root dentin microhardness of extracted vital teeth is 67 VHN(248). The VHN values of all 4 NiTi instruments tested in our study should be enough (at least 5 times harder than dentin) for shaping and cleaning canal walls. This finding of our study is in agreement with a previous study(88). PTN and EdgeFiles revealed the highest VHN values compared with HCM and XP-endoShaper, Up to date, there is no study investigating the Vicker microhardness of EdgeFile and XP-endoShaper, so we cannot compare our results to other kinds of literature. Also, there was little literature that assessed the microhardness of PTN and HCM files. Except for the XP-endoShaper, all of the tested NiTi instruments were ground in both rough and fine stages, with the exception of the XP-endoShaper, which was only ground in fine stages due to the smallest core diameter and the loss of all details if we utilized rough grinding stages. To evaluate the results and find possible methods to enhance the validity of such studies, the outstanding features of these studies were studied and assessed. In confirmed with previous studies showed that the M-Wire instruments had the greatest surface hardness in comparison to conventional superelastic ProFile instruments, which is revealing of higher strength and better wear resistance(249). Also, the corresponding scanning transmission electron microscope examinations of M-Wire blank by the author shown greatly coarser grains, twinning, and a high density of dislocations, which were not detected in early superelastic NiTi wire blanks for conventional instruments(60,249). Elnaghy and Elsaka *et al* compare the mechanical properties of ProTaper Next files (PTN) with Twisted Files (TF) and RaCe (RC). They concluded that PTN revealed the highest microhardness value which improved its resistance to wear compared with TF and RC(173), and the authors explained the reason for that to its unique nano-crystalline martensitic microstructure of M-Wire(60). Elnaghy and Elsaka *et al* a compared the mechanical properties of TRUShape, ProTaper Next X2, ProTaper Gold, and ProTaper Universal F2 instruments, they concluded that PTU had significantly higher surface microhardness values compared with other tested brands, and the second one was PTN(152). Lopes HP *et al* assess the microhardness of endodontic instruments with conventional (RaCe) and CM NiTi alloy(Hyflex CM), they revealed no significant

difference was observed in the microhardness tests(174). Shen *et al* examine the type and location of defects in HyFlex CM instruments after clinical use in a graduate endodontic program and to inspect the impact of clinical use on their metallurgical properties, they founded no significant difference in microhardness was detected between new and used instruments (with and without defects)(51). This could be related to the fact that the manufacturer of HyFlex instruments guarantees that sterilization will restore the instrument's shape, and that more than half of instruments that underwent plastic deformation in simulated use in plastic block canals recovered their original shape after a sterilization cycle(250).



6. CONCLUSIONS:

Within the limitations of this study in vitro, it can be concluded:

1. EdgeFile and XP-endoShaper instruments had superior fatigue resistance and flexibility than PTN and HCM files.
2. The more complexity of the root canal, the greater the impact effects on the CFR of the instruments. In such complexities, researchers concluded that a double canal curvature suggested far more stressful and demanding anatomy than a single curvature. The findings revealed that fatigue builds up quickly in PTN instruments, implying that PTN isn't useful in cases of extreme curvature and challenging canals.
3. Fatigue resistance testing performed at room temperature should be dismissed as meaningless and so obsolete. The temperature could be set to a simulated body temperature, which appears to have an impact on the results of fatigue testing in this study.
4. The body temperature and immersion of NaOCl were shown to play a vital role in the performance of endodontic instruments. It had significant adverse effects on the CFR of EdgeFile and XP-endoShaper instruments.
5. Except for EdgeFile and XP-endoShaper, repeated sterilization cycles had little effect on the CFR of NiTi endodontic instruments. This had a favorable effect on EdgeFile's CFR but a negative effect on XP-endoShaper.
6. The PTN and EdgeFile instruments revealed more resistance to wear compared to others.
7. Clinicians must be cautious when using these findings to clinical practice because no single factor determines the file, and clinicians must understand the properties of different NiTi rotary systems and their implications for use based on root canal clinical conditions.
8. The instruments are only as good as the man who operates them. Therefore, they should be chosen based on the case's requirements, convenience of use, safety, and efficiency.

7. REFERENCES:

1. McCabe JF, Yan Z, Al Naimi OT, Mahmoud G, Rolland SL. Smart materials in dentistry. *Aust Dent J.* 2011;56(SUPPL. 1):3–10.
2. Gutmann JL, Gao Y. Alteration in the inherent metallic and surface properties of nickel-titanium root canal instruments to enhance performance, durability and safety: A focused review. *Int Endod J.* 2012;45(2):113–28.
3. Walia H, Brantley WA, Gerstein H. An initial investigation of the bending and torsional properties of nitinol root canal files. *J Endod.* 1988;14(7):346–51.
4. Ferreira M, Ferreira H, Oliveiros B, Carrilho E. Defects in ProFile rotary nickel-titanium files after clinical use. *Endod Pract Today.* 2012;6(2):113–7.
5. Dentsply. Protaper Next brochure, Dentsply Maillefer 2013. Available at: http://dentsplymea.com/sites/default/files/ProTaper%20NEXT%20brochure_0.pdf.
6. Coltene®Endo. Hyflex CM brochure, Coltene/Whaledent IU. https://www.endoexperience.com/documents/30464A_HYFLEX-CM_bro.pdf.
7. EdgeFile X7, EdgeEndo, USA. Available at: <http://edgeendo.ca/wp-content/uploads/2012/10/EdgeFile-Tip-Cards-Canada-X7.pdf>. :1–2.
8. FKG Dentaire (2016) The XP-endo shaper brochure. Available at: http://www.fkg.ch/sites/default/files/201612_fkg_XPS_brochure_v3_en_web.pdf.
9. Ørstavik D. Apical Periodontitis: Microbial Infection and Host Responses. In: *Essential endodontology*. 2008. p. 3–9.
10. Kakehashi S, Stanley HR, Fitzgerald RJ. The effects of surgical exposures of dental pulps in germ-free and conventional laboratory rats. *Oral Surgery, Oral Med Oral Pathol.* 1965;20(3):340–9.
11. Siqueira Jr JF, Lopes HP. Chemomechanical Preparation. *Treat Endod Infect London Quintessence Publ.* 2011;p236-284.
12. Metzger Z, Solomonov M, Kfir A. The role of mechanical instrumentation in the cleaning of root canals. *Endod Top.* 2013;29(1):87–109.
13. Hülsmann M, Peters OA, Dummer PMH. Mechanical preparation of root canals: shaping goals, techniques and means. *Endod Top.* 2005;10(1):30–76.
14. Lim KC, Webber J. The effect of root canal preparation on the shape of the curved root canal. *Int Endod J.* 1985;18(4):233–9.
15. Cunningham CJ, Senia ES. A three-dimensional study of canal curvatures in the mesial roots of mandibular molars. *J Endod.* 1992;18(6):294–300.
16. Willershausen B, Kasaj A, Tekyatan H, Roehrig B, Briseno B. Radiographic investigation of location and angulation of curvatures in human maxillary incisors. *J Endod.* 2008;34(9):1052–6.
17. Willershausen B, Tekyatan H, Kasaj A, Marroquín BB. Roentgenographic in vitro investigation of frequency and location of curvatures in human maxillary premolars. *J Endod.* 2006;32(4):307–11.
18. Schäfer E, Diez C, Hoppe W, Tepel J. Roentgenographic investigation of frequency and degree of canal curvatures in human permanent teeth. *J Endod.* 2002;28(3):211–6.
19. Schneider SW. A comparison of canal preparations in straight and curved root canals. *Oral surgery, Oral Med Oral Pathol.* 1971;32(2):271–5.
20. Pruett JP, Clement DJ, Carnes Jr DL. Cyclic fatigue testing of nickel-titanium endodontic

- instruments. *J Endod.* 1997;23(2):77–85.
21. Cruse WP, Bellizzi R. A historic review of endodontics, 1689–1963, part 1. *J Endod.* 1980;6(3):495–9.
 22. Zinelis S, Magnissalis EA, Margelos J, Lambrianidis T. Clinical relevance of standardization of endodontic files dimensions according to the ISO 3630-1 specification. *J Endod.* 2002;28(5):367–70.
 23. Buehler WJ, Gilfrich J V, Wiley RC. Effect of low-temperature phase changes on the mechanical properties of alloys near composition TiNi. *J Appl Phys.* 1963;34(5):1475–7.
 24. Buehler WJ, Wiley RC. The properties of TiNi and associated phases NOLTR 61-75. Volume 61; Volume 75 of Naval Ordnance Laboratory White Oak, Md: NOL; 1961.
 25. Andreasen GF, Morrow RE. Laboratory and clinical analyses of nitinol wire. *Am J Orthod Dentofac Orthop.* 1978;73(2):142–51.
 26. Cohen S, Hargreaves KM BL. Principles of Cleaning and Shaping, Endodontic Instruments. In: *Pathways of the Pulp* (10ed) Mosby, Inc: 2011. p. 213, 219.
 27. Weine FS, Kelly RF, Lio PJ. The effect of preparation procedures on original canal shape and on apical foramen shape. *J Endod.* 1975;1(8):255–62.
 28. Tan BT, Messer HH. The quality of apical canal preparation using hand and rotary instruments with specific criteria for enlargement based on initial apical file size. *J Endod.* 2002;28(9):658–64.
 29. De-Deus G, Garcia-Filho P. Influence of the NiTi rotary system on the debridement quality of the root canal space. *Oral Surgery, Oral Med Oral Pathol Oral Radiol Endodontology.* 2009;108(4):e71–6.
 30. Brunson M, Heilborn C, Johnson DJ, Cohenca N. Effect of apical preparation size and preparation taper on irrigant volume delivered by using negative pressure irrigation system. *J Endod.* 2010;36(4):721–4.
 31. Arvaniti IS, Khabbaz MG. Influence of root canal taper on its cleanliness: a scanning electron microscopic study. *J Endod.* 2011;37(6):871–4.
 32. de Gregorio C, Arias A, Navarrete N, del Rio V, Oltra E, Cohenca N. Effect of apical size and taper on volume of irrigant delivered at working length with apical negative pressure at different root curvatures. *J Endod.* 2013;39(1):119–24.
 33. Thompson SA. An overview of nickel–titanium alloys used in dentistry. *Int Endod J.* 2000;33(4):297–310.
 34. DesRoches R, McCormick J, Delemont M. Cyclic properties of superelastic shape memory alloy wires and bars. *J Struct Eng.* 2004;130(1):38–46.
 35. Glosson CR, Haller RH, Dove SB, Carlos E. A comparison of root canal preparations using Ni-Ti hand, Ni-Ti engine-driven, and K-Flex endodontic instruments. *J Endod.* 1995;21(3):146–51.
 36. Gambill JM, Alder M, Carlos E. Comparison of nickel-titanium and stainless steel hand-file instrumentation using computed tomography. *J Endod.* 1996;22(7):369–75.
 37. Gluskin AH, Brown DC, Buchanan LS. A reconstructed computerized tomographic comparison of Ni–Ti rotary GTTM files versus traditional instruments in canals shaped by novice operators. *Int Endod J.* 2001;34(6):476–84.
 38. Haapasalo M, Shen Y. Evolution of nickel–titanium instruments: from past to future. *Endod Top.* 2013;29(1):3–17.
 39. Shaw JA, Churchill CB, Iadicola MA. Tips and tricks for characterizing shape memory alloy wire: Part 1-differential scanning calorimetry and basic phenomena. *Exp Tech.* 2008;32(5):55–62.

40. Young GR, Parashos P, Messer HH. The principles of techniques for cleaning root canals. *Aust Dent J.* 2007;52:S52–63.
41. Schäfer E, Dammaschke T. Development and sequelae of canal transportation. *Endod Top.* 2009;15(1):75–90.
42. Cheung GSP, Liu CSY. A retrospective study of endodontic treatment outcome between nickel-titanium rotary and stainless steel hand filing techniques. *J Endod.* 2009;35(7):938–43.
43. Yared GM, Bou Dagher FE, Machtou P. Influence of rotational speed, torque and operator's proficiency on ProFile failures. *Int Endod J.* 2001;34(1):47–53.
44. Yared GM, Bou Dagher FE, Machtou P, Kulkarni GK. Influence of rotational speed, torque and operator proficiency on failure of Greater Taper files. *Int Endod J.* 2002;35(1):7–12.
45. Shen Y, Zhou HM, Zheng YF, Peng B, Haapasalo M. Current challenges and concepts of the thermomechanical treatment of nickel-titanium instruments. *J Endod.* 2013;39(2):163–72.
46. Miyazaki S, Otsuka K. Deformation and transition behavior associated with the R-phase in Ti-Ni alloys. *Metall Trans A.* 1986;17(1):53–63.
47. Otsuka K, Ren X. Physical metallurgy of Ti-Ni-based shape memory alloys. *Prog Mater Sci.* 2005;50(5):511–678.
48. Dan Ammon, Vincent Shotton, Yong Gao RM. *Endodontic Instruments and Methods of Manufacturing Thereof.* DENTSPLY Int Inc, York, PA, US. 2014;2(12):1–45.
49. Kuhn G, Jordan L. Fatigue and mechanical properties of nickel-titanium endodontic instruments. *J Endod.* 2002;28(10):716–20.
50. Zhou H, Peng B, Zheng Y-F. An overview of the mechanical properties of nickel-titanium endodontic instruments. *Endod Top.* 2013;29(1):42–54.
51. Shen Y, Coil JM, Zhou H, Zheng Y, Haapasalo M. HyFlex nickel-titanium rotary instruments after clinical use: Metallurgical properties. *Int Endod J.* 2013;46(8):720–9.
52. Zupanc J, Vahdat-Pajouh N, Schäfer E. New thermomechanically treated NiTi alloys – a review. *Int Endod J.* 2018;51(10):1088–103.
53. Viana ACD, Chaves Craveiro De Melo M, Guimar De Azevedo Bahia M, Lopes Buono VT. Relationship between flexibility and physical, chemical, and geometric characteristics of rotary nickel-titanium instruments. *Oral Surgery, Oral Med Oral Pathol Oral Radiol Endodontology.* 2010;110(4):527–33.
54. Pereira ESJ, Peixoto IFC, Viana ACD, Oliveira II, Gonzalez BM, Buono VTL, et al. Physical and mechanical properties of a thermomechanically treated NiTi wire used in the manufacture of rotary endodontic instruments. *Int Endod J.* 2012;45(5):469–74.
55. Lopes HP, Elias CN, Vieira VTL, Moreira EJJ, Marques RVL, MacHado De Oliveira JC, et al. Effects of electropolishing surface treatment on the cyclic fatigue resistance of bioactive nickel-titanium rotary instruments. *J Endod.* 2010;36(10):1653–7.
56. Lopes HP, Elias CN, Vieira MVB, Vieira VTL, De Souza LC, Dos Santos AL. Influence of Surface Roughness on the Fatigue Life of Nickel-Titanium Rotary Endodontic Instruments. *J Endod.* 2016;42(6):965–8.
57. Lopes H, Elias C, Vieira M, Vieira V, Inojosa I, Ferreira L. Influence of the surface roughness on the torsional resistance of nickel-titanium rotary endodontic instruments. *ENDO (1 Engl).* 2017;11(1):51–5.
58. Berendt CJ. Method of preparing Nitinol for use in manufacturing instruments with improved fatigue resistance. Sport LLC, PA, US. 2007;1(19):1–15.

59. Braga LCM oreir., Faria Silva AC ristín., Buono VT ade. L, de Azevedo Bahia MG uioma. Impact of heat treatments on the fatigue resistance of different rotary nickel-titanium instruments. *J Endod.* 2014;40(9):1494–7.
60. Ye J, Gao Y. Metallurgical characterization of M-Wire nickel-titanium shape memory alloy used for endodontic rotary instruments during low-cycle fatigue. *J Endod.* 2012;38(1):105–7.
61. Pereira ESJ, Gomes RO, Leroy AMF, Singh R, Peters OA, Bahia MGA, et al. Mechanical behavior of M-Wire and conventional NiTi wire used to manufacture rotary endodontic instruments. *Dent Mater.* 2013;29(12):e318–24.
62. Gao Y, Shotton V, Wilkinson K, Phillips G, Ben Johnson W. Effects of raw material and rotational speed on the cyclic fatigue of profile vortex rotary instruments. *J Endod.* 2010;36(7):1205–9.
63. Larsen CM, Watanabe I, Glickman GN, He J. Cyclic Fatigue Analysis of a New Generation of Nickel Titanium Rotary Instruments. *J Endod.* 2009;35(3):401–3.
64. Hou XM, Yahata Y, Hayashi Y, Ebihara A, Hanawa T, Suda H. Phase transformation behaviour and bending property of twisted nickel-titanium endodontic instruments. *Int Endod J.* 2011;44(3):253–8.
65. Pedullà E, Grande NM, Plotino G, Pappalardo A, Rapisarda E. Cyclic fatigue resistance of three different nickel-titanium instruments after immersion in sodium hypochlorite. *J Endod.* 2011;37(8):1139–42.
66. Elsaka SE, Elnaghy AM, Badr AE. Torsional and bending resistance of WaveOne Gold, Reciproc and twisted file adaptive instruments. *Int Endod J.* 2017;50(11):1077–83.
67. Choi J, Oh S, Kim Y-C, Jee K-K, Kum K, Chang S. Fracture resistance of K3 nickel-titanium files made from different thermal treatments. *Bioinorg Chem Appl.* 2016;2016:1–6.
68. Rejula F, Christalin R, Ahmed W, Dinakaran S, Gopinathan AS, Babu A. Measure and compare the degree of root canal transportation and canal-centering ability of twisted, protaper, and conventional stainless steel k files using spiral computed tomography: An in vitro study. *J Contemp Dent Pract.* 2017;18(6):463–9.
69. McKelvey AL, Ritchie RO. Fatigue-crack growth behavior in the superelastic and shape-memory alloy nitinol. *Metall Mater Trans A.* 2001;32(3):731–43.
70. Kaack M. Elastische Eigenschaften von NiTi- Formgedächtnis-Legierungen (PhD Thesis). Bochum, Ger Ruhr-Universität Bochum. 2002.
71. Zhou HM, Shen Y, Zheng W, Li L, Zheng YF, Haapasalo M. Mechanical properties of controlled memory and superelastic nickel-titanium wires used in the manufacture of rotary endodontic instruments. *J Endod.* 2012;38(11):1535–40.
72. Iacono F, Pirani C, Generali L, Bolelli G, Sassatelli P, Lusvarghi L, et al. Structural analysis of HyFlex EDM instruments. *Int Endod J.* 2017;50(3):303–13.
73. Pereira ÉSJ, Viana ACD, Buono VTL, Peters OA, Azevedo Bahia MG De. Behavior of nickel-titanium instruments manufactured with different thermal treatments. *J Endod.* 2015;41(1):67–71.
74. Soares Renata G, Lopes Hélio P, Elias Carlos N, Viera Márcia V B, Vieira Victor T L, de Paula Cintia B AFRF. Comparative study of the mechanical properties of instruments made of conventional, M-wire, R-phase, and controlled memory nickel-titanium alloys. *ENDO - Endod Pract Today.* 2017;11(4):271–7.
75. Peters OA, Morgental RD, Schulze KA, Paqué F, Kopper PMP, Vier-Pelisser F V. Determining cutting efficiency of nickel-titanium coronal flaring instruments used in lateral action. *Int Endod J.* 2014;47(6):505–13.
76. Plotino G, Testarelli L, Al-Sudani D, Pongione G, Grande NM, Gambarini G. Fatigue resistance of rotary instruments manufactured using different nickel-titanium alloys: A comparative study.

Odontology. 2014;102(1):31–5.

77. Pirani C, Iacono F, Generali L, Sassatelli P, Nucci C, Lusvarghi L, et al. HyFlex EDM: Superficial features, metallurgical analysis and fatigue resistance of innovative electro discharge machined NiTi rotary instruments. *Int Endod J*. 2016;49(5):483–93.
78. Coltene®. Hyflex CM brochure, Coltene/Whaledent, Inc. Available at: <https://www.coltene.com/products/endodontics/rotary-files/hyflex-rotary-files/hyflexTM-cm-niti-files/>. Available from: <https://www.coltene.com/pim/DOC/BRO/docbro6849-03-18-es-hyflex-cm-edm-a4sesaindv1.pdf>
79. Bojorquez B, Marloth RT, Es-Said OS. Formation of a crater in the workpiece on an electrical discharge machine. *Eng Fail Anal*. 2002;9(1):93–7.
80. Daneshmand S, Kahrizi EF, Abedi E, Mir Abdolhosseini M. Influence of machining parameters on electro discharge machining of NiTi shape memory alloys. *Int J Electrochem Sci*. 2013;8(3):3095–104.
81. Singh S, Maheshwari S, Pandey PC. Some investigations into the electric discharge machining of hardened tool steel using different electrode materials. *J Mater Process Technol*. 2004;149(1–3):272–7.
82. Uslu G, Özyürek T, Yılmaz K. Comparison of Alterations in the Surface Topographies of HyFlex CM and HyFlex EDM Nickel-titanium Files after Root Canal Preparation: A Three-dimensional Optical Profilometry Study. *J Endod*. 2018;44(1):115–9.
83. Pedullà E, Lo Savio F, Boninelli S, Plotino G, Grande NM, La Rosa G, et al. Torsional and Cyclic Fatigue Resistance of a New Nickel-Titanium Instrument Manufactured by Electrical Discharge Machining. *J Endod*. 2016;42(1):156–9.
84. Pinheiro SR, Alcade MP, Vivacqua-Gomes N, Bramante CM, Vivan RR, H. MA, et al. Evaluation of apical transportation and centering ability of five thermally treated NiTi rotary systems. *Int Endod J*. 2018;38(1):42–9.
85. Plotino G, Grande NM, Cotti E, Testarelli L, Gambarini G. Blue treatment enhances cyclic fatigue resistance of vortex nickel-titanium rotary files. *J Endod*. 2014;40(9):1451–3.
86. Hu W, Whitten B, Sedgley C, Svec T. Effect of three NiTi files on transportation of the apical foramen. *Int Endod J*. 2014;47(11):1064–71.
87. Shen Y, Zhou H, Coil JM, Aljazaeri B, Buttar R, Wang Z, et al. ProFile vortex and vortex blue nickel-titanium rotary instruments after clinical use. *J Endod*. 2015;41(6):937–42.
88. Gao Y, Gutmann JL, Wilkinson K, Maxwell R, Ammon D. Evaluation of the impact of raw materials on the fatigue and mechanical properties of profile vortex rotary instruments. *J Endod*. 2012;38(3):398–401.
89. De-Deus G, Silva EJNL, Vieira VTL, Belladonna FG, Elias CN, Plotino G, et al. Blue Thermomechanical Treatment Optimizes Fatigue Resistance and Flexibility of the Reciproc Files. *J Endod*. 2017;43(3):462–6.
90. Hieawy A, Haapasalo M, Zhou H, Wang ZJ, Shen Y. Phase Transformation Behavior and Resistance to Bending and Cyclic Fatigue of ProTaper Gold and ProTaper Universal Instruments. *J Endod*. 2015;41(7):1134–8.
91. Elnaghy A, Elsaka S. Cyclic fatigue resistance of XP-endo Shaper compared with different nickel-titanium alloy instruments. *Clin Oral Investig*. 2018;22(3):1433–7.
92. Silva EJNL, Vieira VTL, Belladonna FG, Zuolo A de S, Antunes H dos S, Cavalcante DM, et al. Cyclic and Torsional Fatigue Resistance of XP-endo Shaper and TRUShape Instruments. *J Endod*. 2018;44(1):168–72.
93. Elnaghy AM, Elsaka SE. Torsional resistance of XP-endo Shaper at body temperature compared

- with several nickel- titanium rotary instruments. *Int Endod J.* 2018;51(5):572–6.
94. Ninan E, Berzins DW. Torsion and bending properties of shape memory and superelastic nickel-titanium rotary instruments. *J Endod.* 2013;39(1):101–4.
 95. Sattapan B, Nervo GJ, Palamara JEA, Messer HH. Defects in rotary nickel-titanium files after clinical use. *J Endod.* 2000;26(3):161–5.
 96. Cheung GSP. Instrument fracture: mechanisms, removal of fragments, and clinical outcomes. *Endod Top.* 2007;16(1):1–26.
 97. Parashos P, Gordon I, Messer HH. Factors influencing defects of rotary nickel-titanium endodontic instruments after clinical use. *J Endod.* 2004;30(10):722–5.
 98. Peng B, Shen Y, Cheung GSP, Xia TJ. Defects in ProTaper S1 instruments after clinical use: Longitudinal examination. *Int Endod J.* 2005;38(8):550–7.
 99. G. S. P. Cheung¹, B. Peng², Z. Bian² YS& BWD. Defects in ProTaper S1 instruments after clinical use: fractographic examination. *Int Endod J.* 2005;38(8):550–7.
 100. Parashos P, Messer HH. Rotary NiTi Instrument Fracture and its Consequences. *J Endod.* 2006;32(11):1031–43.
 101. Lee MH, Versluis A, Kim BM, Lee CJ, Hur B, Kim HC. Correlation between experimental cyclic fatigue resistance and numerical stress analysis for nickel-titanium rotary files. *J Endod.* 2011;37(8):1152–7.
 102. Figueiredo AM, Modenesi P, Buono V. Low-cycle fatigue life of superelastic NiTi wires. *Int J Fatigue.* 2009;31(4):751–8.
 103. Shen Y, Qian W, Abtin H, Gao Y, Haapasalo M. Fatigue testing of controlled memory wire nickel-titanium rotary instruments. *J Endod.* 2011;37(7):997–1001.
 104. Patiño PV, Biedma BM, Liébana CR, Cantatore G, Bahillo JG. The influence of a manual glide path on the separation rate of NiTi rotary instruments. *J Endod.* 2005;31(2):114–6.
 105. Roland DD, Andelin WE, Browning DF, Hsu GHR, Torabinejad M. The effect of preflaring on the rates of separation for 0.04 taper nickel titanium rotary instruments. *J Endod.* 2002;28(7):543–5.
 106. Schrader C, Peters OA. Analysis of torque and force with differently tapered rotary endodontic instruments in vitro. *J Endod.* 2005;31(2):120–3.
 107. Gambarini G. Cyclic fatigue of nickel-titanium rotary instruments after clinical use with low- and high-torque endodontic motors. *J Endod.* 2001;27(12):772–4.
 108. Berutti E, Negro AR, Lendini M, Pasqualini D. Influence of manual preflaring and torque on the failure rate of ProTaper rotary instruments. *J Endod.* 2004;30(4):228–30.
 109. Herold KS, Johnson BR, Wenckus CS. A Scanning Electron Microscopy Evaluation of Microfractures, Deformation and Separation in EndoSequence and Profile Nickel-Titanium Rotary Files Using an Extracted Molar Tooth Model. *J Endod.* 2007;33(6):712–4.
 110. Li UM, Lee BS, Shih CT, Lan WH, Lin CP. Cyclic fatigue of endodontic nickel titanium rotary instruments: Static and dynamic tests. *J Endod.* 2002;28(6):448–51.
 111. Grande NM, Plotino G, Pecci R, Bedini R, Malagnino VA, Somma F. Cyclic fatigue resistance and three-dimensional analysis of instruments from two nickel-titanium rotary systems. *Int Endod J.* 2006;39(10):755–63.
 112. Peters OA. Current Challenges and Concepts in the Preparation of Root Canal Systems: A Review. *J Endod.* 2004;Aug;30(8):559-67.
 113. Peters OA, Kappeler S, Bucher W, Barbakow F. Engine-driven preparation of curved root canals: Measuring cyclic fatigue and other physical parameters. *Aust Endod J.* 2002;28(1):11–7.

114. Booth JR, Scheetz JP, Lemons JE, Eleazer PD. A comparison of torque required to fracture three different nickel-titanium rotary instruments around curves of the same angle but of different radius when bound at the tip. *J Endod.* 2003;29(1):55–7.
115. Iqbal MK, Kohli MR, Kim JS. A Retrospective Clinical Study of Incidence of Root Canal Instrument Separation in an Endodontics Graduate Program: A PennEndo Database Study. *J Endod.* 2006;32(11):1048–52.
116. Mize SB, Clement DJ, Pruett JP, Carnes DL. Effect of sterilization on cyclic fatigue of rotary nickel-titanium endodontic instruments. *J Endod.* 1998;24(12):843–7.
117. Rapisarda E, Bonaccorso A, Tripi TR, Condorelli GG. Effect of sterilization on the cutting efficiency of rotary nickel-titanium endodontic files. *Oral Surg Oral Med Oral Pathol Oral Radiol Endod.* 1999;88(3):343–7.
118. Yared GM, Bou Dagher FE, Machtou P. Cyclic fatigue of ProFile rotary instruments after clinical use. *Int Endod J.* 2000;33(3):204–7.
119. Silvaggio J. Effect of heat sterilization on the torsional properties of rotary nickel-titanium endodontic files. *J Endod.* 1997;23(12):731–4.
120. Dioguardi M, Sovereto D, Aiuto R, Laino L, Illuzzi G, Laneve E, et al. Effects of hot sterilization on torsional properties of endodontic instruments: Systematic review with meta-analysis. *Materials (Basel).* 2019;12(13):1–15.
121. Zhao D, Shen Y, Peng B, Haapasalo M. Effect of autoclave sterilization on the cyclic fatigue resistance of thermally treated Nickel–Titanium instruments. *Int Endod J.* 2016;49(10):990–5.
122. O’Hoy PYZ, Messer HH, Palamara JEA. The effect of cleaning procedures on fracture properties and corrosion of NiTi files. *Int Endod J.* 2003;36(11):724–32.
123. Linsuwanont P, Parashos P, Messer HH. Cleaning of rotary nickel-titanium endodontic instruments. *Int Endod J.* 2004;37(1):19–28.
124. Shen Y, Haapasalo M, Cheung GSP, Peng B. Defects in Nickel-Titanium Instruments after Clinical Use. Part 1: Relationship between Observed Imperfections and Factors Leading to Such Defects in a Cohort Study. *J Endod.* 2009;35(1):129–32.
125. Turpin YL, Chagneau F, Vulcain JM. Impact of two theoretical cross-sections on torsional and bending stresses of nickel-titanium root canal instrument models. *J Endod.* 2000;26(7):414–7.
126. Berutti E, Chiandussi G, Gaviglio I, Ibba A. Comparative analysis of torsional and bending stresses in two mathematical models of nickel-titanium rotary instruments: ProTaper versus ProFile. *J Endod.* 2003;29(1):15–9.
127. Cheung GSP, Darvell BW. Low-cycle fatigue of NiTi rotary instruments of various cross-sectional shapes. *Int Endod J.* 2007;40(8):626–32.
128. Wolcott S, Wolcott J, Ishley D, Kennedy W, Johnson S, Minnich S, et al. Separation Incidence of Protaper Rotary Instruments: A Large Cohort Clinical Evaluation. *J Endod.* 2006;32(12):1139–41.
129. Kuhn G, Tavernier B, Jordan L. Influence of structure on nickel-titanium endodontic instruments failure. *J Endod.* 2001;27(8):516–20.
130. Dosanjh A, Paurazas S, Askar M. The Effect of Temperature on Cyclic Fatigue of Nickel-titanium Rotary Endodontic Instruments. *J Endod.* 2017;43(5):823–6.
131. McGuigan MB, Louca C, Duncan HF. Endodontic instrument fracture: causes and prevention. *Br Dent J.* 2013;214(7):341–8.
132. Spili P, Parashos P, Messer HH (Univ of Melbourne, Victoria A. The Impact of Instrument Fracture on Outcome of Endodontic Treatment. *J Endod.* 2005;31(12):845–50.

133. Di Fiore PM, Genov KA, Komaroff E, Li Y, Lin L. Nickel-titanium rotary instrument fracture: A clinical practice assessment. *Int Endod J.* 2006;39(9):700–8.
134. Grossman LI. Guidelines for the prevention of fracture of root canal instruments. *Oral Surgery, Oral Med Oral Pathol.* 1969;28(5):746–52.
135. Panitvisai P, Parunnit P, Sathorn C, Messer HH. Impact of a Retained Instrument on Treatment Outcome: A Systematic Review and Meta-analysis. *J Endod.* 2010;36(5):775–80.
136. Singh K, Bindra SS, Singh G, Kaur H. Endodontic rotary systems - A Review. *J Adv Med Dent Sci Res.* 2016;4(4):62–6.
137. Caicedo DR, Clark SJ. Clinical HyFlex ® CM rotary files : an excellent innovation for endodontic treatment. *Endod Prac.* 2016;4(6):10–7.
138. Hansen CMU. Torsion and Bending Properties of EdgeEndo Files (Master's Theses). Milwaukee, Wisconsin, Marquette Univ. 2016.
139. Nguyen HH, Fong H, Paranjpe A, Flake NM, Johnson JD, Peters OA. Evaluation of the resistance to cyclic fatigue among protaper next, ProTaper universal, and vortex blue rotary instruments. *J Endod.* 2014;40(8):1190–3.
140. Pérez-Higueras JJ, Arias A, de la Macorra JC, Peters OA. Differences in cyclic fatigue resistance between ProTaper Next and ProTaper Universal instruments at different levels. *J Endod.* 2014;40(9):1477–81.
141. Elnaghy AM. Cyclic fatigue resistance of ProTaper Next nickel-titanium rotary files. *Int Endod J.* 2014;47(11):1034–9.
142. Pedullà E, Lo Savio F, Boninelli S, Plotino G, Grande NM, Rapisarda E, et al. Influence of cyclic torsional preloading on cyclic fatigue resistance of nickel - titanium instruments. *Int Endod J.* 2015;48(11):1043–50.
143. Capar ID, Ertas H, Arslan H. Comparison of cyclic fatigue resistance of novel nickel-titanium rotary instruments. *Aust Endod J.* 2015;41(1):24–8.
144. Peng C, Hui WU, Wang L, Xin HU, Deng S, Li C, et al. Cyclic fatigue resistance of two nickel-titanium instruments in different curving angles: a comparative study. *Braz Oral Res.* 2015;29(1):1–7.
145. Uygun AD, Kol E, Topcu MKC, Seckin F, Ersoy I, Tanriver M. Variations in cyclic fatigue resistance among ProTaper Gold, ProTaper Next and ProTaper Universal instruments at different levels. *Int Endod J.* 2016;49(5):494–9.
146. De Vasconcelos RA, Murphy S, Carvalho CAT, Govindjee RG, Govindjee S, Peters OA. Evidence for Reduced Fatigue Resistance of Contemporary Rotary Instruments Exposed to Body Temperature. *J Endod.* 2016;42(5):782–7.
147. Topçuoğlu HS, Topçuoğlu G, Akti A, Düzgün S. In Vitro Comparison of Cyclic Fatigue Resistance of ProTaper Next, HyFlex CM, OneShape, and ProTaper Universal Instruments in a Canal with a Double Curvature. *J Endod.* 2016;42(6):969–71.
148. Elbatouty KM, Elbatal LM, Obeid MM. Cyclic fatigue resistance of ProTaper Next and NRT nickel titanium rotary files. *ENDO-Endodontic Pract Today.* 2016;10(2):89–94.
149. Pedullà E, Lizio A, Scibilia M, Grande NM, Plotino G, Boninelli S, et al. Cyclic fatigue resistance of two nickel–titanium rotary instruments in interrupted rotation. *Int Endod J.* 2017;50(2):194–201.
150. Ozyurek T. Comparison of the Cyclic Fatigue Resistance of Nickel-Titanium Rotary Instruments Manufactured using Controlled Memory Wire. *Turkish Endod J.* 2017;2(1):5–9.
151. Cai JJ, Tang XN, Ge JY. Effect of irrigation on surface roughness and fatigue resistance of controlled memory wire nickel-titanium instruments. *Int Endod J.* 2017;50(7):718–24.

152. Elnaghy AM, Elsaka SE. Laboratory comparison of the mechanical properties of TRUShape with several nickel-titanium rotary instruments. *Int Endod J*. 2017;50(8):805–12.
153. Özyürek T, Yılmaz K, Uslu G. The effects of autoclave sterilization on the cyclic fatigue resistance of ProTaper Universal, ProTaper Next, and ProTaper Gold nickel-titanium instruments. *Restor Dent Endod*. 2017;42(4):301–8.
154. Adiguzel M, Isken I, Pamukcu II. Comparison of cyclic fatigue resistance of XP-endo Shaper, HyFlex CM, FlexMaster and Race instruments. *J Dent Res Dent Clin Dent Prospects*. 2018;12(3):208–12.
155. Keskin C, Inan U, Guler DH, Kalyoncuoglu E. Cyclic Fatigue Resistance of XP-Endo Shaper, K3XF, and ProTaper Gold Nickel-titanium Instruments. *J Endod*. 2018;44(7):1164–7.
156. Pedullà E, Benites A, La Rosa GM, Plotino G, Grande NM, Rapisarda E, et al. Cyclic Fatigue Resistance of Heat-treated Nickel-titanium Instruments after Immersion in Sodium Hypochlorite and/or Sterilization. *J Endod*. 2018;44(4):648–53.
157. Pedullà E, Corsentino G, Ambu E, Rovai F, Campedelli F, Rapisarda S, et al. Influence of continuous rotation or reciprocation of Optimum Torque Reverse motion on cyclic fatigue resistance of nickel-titanium rotary instruments. *Int Endod J*. 2018 May;51(5):522–8.
158. Shen Y, Huang X, Wang Z, Wei X, Haapasalo M. Low Environmental Temperature Influences the Fatigue Resistance of Nickel-titanium Files. *J Endod*. 2018;44(4):626–9.
159. Bueno CRE, Cury MTS, Vasques AMV, Sivieri-Araújo G, Jacinto RC, Gomes-Filho JE, et al. Cyclic fatigue resistance of novel Genius and Edgefile nickel-titanium reciprocating instruments. *Braz Oral Res*. 2019;33(e028):1–9.
160. Bhatt A, Rajkumar B. A comparative evaluation of cyclic fatigue resistance for different endodontic NiTi rotary files: An in-vitro study. *J Oral Biol Craniofacial Res*. 2019;9(2):119–21.
161. Aksel H. CYCLIC FATIGUE RESISTANCE OF XP SHAPER AND HYFLEX EDM AFTER EXPOSURE TO SODIUM HYPOCHLORITE OR RC PREP. *Clin Dent Res*. 2019;43(3):93–9.
162. Olcay K, Eyuboglu TF, Erkan E. Cyclic fatigue resistance of waveone gold, protaper next and 2shape nickel titanium rotary instruments using a reliable method for measuring temperature. *Niger J Clin Pract*. 2019;22(10):1335–40.
163. Palma PJ, Messias A, Cerqueira AR, Tavares LD, Caramelo F, Roseiro L, et al. Cyclic fatigue resistance of three rotary file systems in a dynamic model after immersion in sodium hypochlorite. *Odontology*. 2019;107(3):324–32.
164. Ertuğrul İF. Effect of sodium hypochlorite on the cyclic fatigue resistance: A scanning electron microscopy evaluation. *Microsc Res Tech*. 2019;82(12):2089–94.
165. Cardoso RM, Alves NCC, de Menezes SEAC, Batista SM, Vieira TM, Rocha GNE, et al. Influence of Temperature on the Cyclic Fatigue of Nickel–Titanium Instruments with Different Heat Treatments on Severely Curved Canals. *Dent Pr*. 2019;20(6):697–701.
166. Elnaghy AM, Elsaka SE, Mandorah AO. In vitro comparison of cyclic fatigue resistance of TruNatomy in single and double curvature canals compared with different nickel-titanium rotary instruments. *BMC Oral Health*. 2020;20(1):38.
167. Riyahi AM, Bashiri A, Alshahrani K, Alshahrani S, Alamri HM, Al-Sudani D. Cyclic Fatigue Comparison of TruNatomy, Twisted File, and ProTaper Next Rotary Systems. *Int J Dent*. 2020;2020:5–8.
168. Uslu G, Gundogar M, Özyürek T, Plotino G. Cyclic fatigue resistance of reduced-taper nickel-titanium (NiTi) instruments in doubled-curved (S-shaped) canals at body temperature. *Prospect Dent Clin Dent Res Dent J*. 2020;14(2):1–5.
169. Gündoğar M, Uslu G, Özyürek T, Plotino G. Comparison of the cyclic fatigue resistance of VDW.

- ROTATE, TruNatomy, 2Shape, and HyFlex CM nickel-titanium rotary files at body temperature. *Restor Dent Endod*. 2020;45(3):1–8.
170. Topçuoğlu HS, Topçuoğlu G, Kafdağ Ö, Balkaya H. Effect of two different temperatures on resistance to cyclic fatigue of one Curve, EdgeFile, HyFlex CM and ProTaper next files. *Aust Endod J*. 2020;46(1):68–72.
 171. Pongione G, Pompa G, Milana V, Di Carlo S, Giansiracusa A, Nicolini E, et al. Flexibility and resistance to cyclic fatigue of endodontic instruments made with different nickel-titanium alloys: a comparative test. *Ann Stomatol (Roma)*. 2012;3(3–4):119–22.
 172. De Arruda Santos L, De Azevedo Bahia MG, De Las Casas EB, Buono VTL. Comparison of the mechanical behavior between controlled memory and superelastic nickel-titanium files via finite element analysis. *J Endod*. 2013;39(11):1444–7.
 173. Elnaghy AM, Elsaka SE. Assessment of the mechanical properties of ProTaper next nickel-titanium rotary files. *J Endod*. 2014;40(11):1830–4.
 174. Lopes HP, Vieira MVB, Elias CN, Villagra RM VV, LC. S. Evaluation of physicochemical and mechanical properties of NiTi endodontic instruments made with conventional and controlled-memory alloys. *Dent Press Endod*. 2016;6(2):28–33.
 175. Goo HJ, Kwak SW, Ha JH, Pedullà E, Kim HC. Mechanical Properties of Various Heat-treated Nickel-titanium Rotary Instruments. *J Endod*. 2017;43(11):1872–7.
 176. Plotino G, Grande NM, Cordaro M, Testarelli L, Gambarini G. A Review of Cyclic Fatigue Testing of Nickel-Titanium Rotary Instruments. *J Endod*. 2009;35(11):1469–76.
 177. Dederich DN, Zakariasen KL. The effects of cyclical axial motion on rotary endodontic instrument fatigue. *Oral Surgery, Oral Med Oral Pathol*. 1986;61(2):192–6.
 178. Haïkel Y, Serfaty R, Bateman G, Senger B, Allemann C. Dynamic and cyclic fatigue of engine-driven rotary nickel-titanium endodontic instruments. *J Endod*. 1999;25(6):434–40.
 179. Cheung GSP, Shen Y, Darvell BW. Does Electropolishing Improve the Low-cycle Fatigue Behavior of a Nickel-Titanium Rotary Instrument in Hypochlorite? *J Endod*. 2007;33(10):1217–21.
 180. Cheung GSP, Darvell BW. Fatigue testing of a NiTi rotary instrument. Part 1: Strain-life relationship. *Int Endod J*. 2007;40(8):612–8.
 181. Cheung GSP, Shen Y, Darvell BW. Effect of Environment on Low-cycle Fatigue of a Nickel-Titanium Instrument. *J Endod*. 2007;33(12):1433–7.
 182. Plotino G, Grande NM, Cordaro M, Testarelli L, Gambarini G. Measurement of the trajectory of different NiTi rotary instruments in an artificial canal specifically designed for cyclic fatigue tests. *Oral Surgery, Oral Med Oral Pathol Oral Radiol Endodontology*. 2009;108(3):e152–6.
 183. Plotino G, Grande NM, Mazza C, Petrovic R, Testarelli L, Gambarini G. Influence of size and taper of artificial canals on the trajectory of NiTi rotary instruments in cyclic fatigue studies. *Oral Surgery, Oral Med Oral Pathol Oral Radiol Endodontology*. 2010;109(1):e60–6.
 184. 3630-1 ISO. Dentistry–Root canal instruments–Part 1: General requirements and test methods. *Int Organ Stand*. 2019;Third edit:1–36.
 185. Kwak S-W, Ha J-H, Lee W, Kim S-K, Kim H-C. Buckling resistance, bending stiffness, and torsional resistance of various instruments for canal exploration and glide path preparation. *Restor Dent Endod*. 2014;39(4):270.
 186. Melo MCC, Pereira ESJ, Viana ACD, Fonseca AMA, Buono VTL, Bahia MGA. Dimensional characterization and mechanical behaviour of K3 rotary instruments. *Int Endod J*. 2008;41(4):329–38.

187. Gambarini G, Plotino G, Grande NM, Al-Sudani D, De Luca M, Testarelli L. Mechanical properties of nickel-titanium rotary instruments produced with a new manufacturing technique. *Int Endod J*. 2011;44(4):337–41.
188. Selin CMT. Flexibility of Various Nickel-Titanium Rotary Endodontic Files (Master's Theses). Milwaukee, Wisconsin, Marquette Univ. 2014.
189. Oh S, Kum KY, Cho K, Lee SH, You SH, Go J, et al. Torsional and Bending Properties of v Taper 2H, ProTaper NEXT, NRT, and One Shape. *Biomed Res Int*. 2019;2019:1–8.
190. Seago ST, Bergeron BE, Kirkpatrick TC, Roberts MD, Roberts HW, Himel VT, et al. Effect of Repeated Simulated Clinical Use and Sterilization on the Cutting Efficiency and Flexibility of Hyflex CM Nickel-Titanium Rotary Files. *J Endod*. 2015;41(5):725–8.
191. Scelza P, Harry D, Silva LE smerald. da, Barbosa IB asto., Scelza MZ accar. A comparison of two reciprocating instruments using bending stress and cyclic fatigue tests. *Braz Oral Res*. 2015;29(1):1–7.
192. ASTM. E3-11 Standard Guide for Preparation of Metallographic Specimens 1. ASTM Int. 2011;i(Reapproved):1–12.
193. Elnaghy AM, Elsaka SE. Mechanical properties of ProTaper Gold nickel-titanium rotary instruments. *Int Endod J*. 2016;49(11):1073–8.
194. Al-Sudani D, Grande NM, Plotino G, Pompa G, Di Carlo S, Testarelli L, et al. Cyclic fatigue of nickel-titanium rotary instruments in a double (S-shaped) simulated curvature. *J Endod*. 2012;38(7):987–9.
195. Plotino G, Costanzo A, Grande NM, Petrovic R, Testarelli L, Gambarini G. Experimental evaluation on the influence of autoclave sterilization on the cyclic fatigue of new nickel-titanium rotary instruments. *J Endod*. 2012;38(2):222–5.
196. Pirani C, Cirulli PP, Chersoni S, Micele L, Ruggeri O, Prati C. Cyclic fatigue testing and metallographic analysis of nickel-titanium rotary instruments. *J Endod*. 2011;37(7):1013–6.
197. Abd ElHamid H. Cyclic Fatigue Resistance of Newly Introduced Surface and Thermal Treated Nickel-Titanium Rotary Files. *Egypt Dent J*. 2020;66(1):683–94.
198. Kim HC, Yum J, Hur B, Cheung GSP. Cyclic Fatigue and Fracture Characteristics of Ground and Twisted Nickel-Titanium Rotary Files. *J Endod*. 2010;36(1):147–52.
199. El-Anwar MI, Mandorah AO, Yousief SA, Soliman TA, Abd El-Wahab TM. A finite element study on the mechanical behavior of reciprocating endodontic files. *Brazilian J Oral Sci*. 2015;14(1):52–9.
200. Lopes HP, Gambarra-Soares T, Elias CN, Siqueira JF, Inojosa IFJ, Lopes WSP, et al. Comparison of the mechanical properties of rotary instruments made of conventional nickel-titanium wire, M-Wire, or nickel-titanium alloy in R-phase. *J Endod*. 2013;39(4):516–20.
201. Gambarini G, Gergi R, Naaman A, Osta N, Al Sudani D. Cyclic fatigue analysis of twisted file rotary NiTi instruments used in reciprocating motion. *Int Endod J*. 2012;45(9):802–6.
202. Shen Y, Cheung GSP, Bian Z, Peng B. Comparison of defects in ProFile and ProTaper systems after clinical use. *J Endod*. 2006;32(1):61–5.
203. Cheung GSP, Zhang EW, Zheng YF. A numerical method for predicting the bending fatigue life of NiTi and stainless steel root canal instruments. *Int Endod J*. 2011;44(4):357–61.
204. Ajuz NCC, Armada L, Gonçalves LS, Debelian G, Siqueira JF. Glide path preparation in s-shaped canals with rotary pathfinding nickel-titanium instruments. *J Endod*. 2013;39(4):534–7.
205. Burroughs JR, Bergeron BE, Roberts MD, Hagan JL, Himel VT. Shaping ability of three nickel-titanium endodontic file systems in simulated s-shaped root canals. *J Endod*. 2012;38(12):1618–

- 21.
206. Hülsmann M, Donnermeyer D, Schäfer E. A critical appraisal of studies on cyclic fatigue resistance of engine-driven endodontic instruments. *Int Endod J.* 2019;52(10):1427–45.
207. S El-Din, M Saber AF. Effect of thermal treatment on the flexural resistance of mechanically pre-fatigued NiTi rotary endodontic files. *ENDO (l Engl).* 2011;5(2):145–50.
208. Pedullà E, Grande NM, Plotino G, Gambarini G, Rapisarda E. Influence of continuous or reciprocating motion on cyclic fatigue resistance of 4 different nickel-titanium rotary instruments. *J Endod.* 2013;39(2):258–61.
209. Zhang EW, Cheung GSP, Zheng YF. Influence of cross-sectional design and dimension on mechanical behavior of nickel-titanium instruments under torsion and bending: A numerical analysis. *J Endod.* 2010;36(8):1394–8.
210. Lopes HP, Ferreira AAP, Elias CN, Moreira EJJ, Machado de Oliveira JC, Siqueira JF. Influence of Rotational Speed on the Cyclic Fatigue of Rotary Nickel-Titanium Endodontic Instruments. *J Endod.* 2009;35(7):1013–6.
211. Zelada G, Varela P, Martín B, Bahillo JG, Magán F, Ahn S. The effect of rotational speed and the curvature of root canals on the breakage of rotary endodontic instruments. *J Endod.* 2002;28(7):540–2.
212. Pedullà E, Plotino G, Grande NM, Scibilia M, Pappalardo A, Malagnino VA, et al. Influence of rotational speed on the cyclic fatigue of Mtwo instruments. *Int Endod J.* 2014;47(6):514–9.
213. Daughterty DW, Gound TG, Corner TL. Comparison of fracture rate, deformation rate, and efficiency between rotary endodontic instruments driven at 150 rpm and 350 rpm. *J Endod.* 2001;27(2):93–5.
214. Plotino G, Grande NM, Melo MC, Bahia MG, Testarelli L, Gambarini G. Cyclic fatigue of NiTi rotary instruments in a simulated apical abrupt curvature. *Int Endod J.* 2010;43(3):226–30.
215. Lopes HP, Vieira MVB, Elias CN, Siqueira JF, Gonçalves LS, Vieira VTL. Location of the canal curvature and its influence on the resistance to fatigue fracture of two rotary nickel-titanium endodontic instruments. *ENDO (l Engl).* 2012;6(4):1–6.
216. Duke F, Shen Y, Zhou H, Ruse ND, Wang ZJ, Hieawy A, et al. Cyclic fatigue of ProFile vortex and vortex blue nickel-titanium files in single and double curvatures. *J Endod.* 2015;41(10):1686–90.
217. Elnaghy AM, Elsaka SE. Effect of sodium hypochlorite and saline on cyclic fatigue resistance of WaveOne Gold and Reciproc reciprocating instruments. *Int Endod J.* 2017;50(10):991–8.
218. Zeltner M, Peters OA, Paqué F. Temperature Changes During Ultrasonic Irrigation with Different Inserts and Modes of Activation. *J Endod.* 2009;35(4):573–7.
219. Fayyad DM, Mahran AH. Atomic force microscopic evaluation of nanostructure alterations of rotary NiTi instruments after immersion in irrigating solutions. *Int Endod J.* 2014;47(6):567–73.
220. Cramer SD, Covino BS. Corrosion: Fundamentals, Testing, and Protection. *Handb Mater Park OH ASM Int.* 2003;13A:1–1135.
221. Berutti E, Angelini E, Rigolone M, Migliaretti G, Pasqualini D. Influence of sodium hypochlorite on fracture properties and corrosion of ProTaper Rotary instruments. *Int Endod J.* 2006;39(9):693–9.
222. Bulem ÜK, Keceli AD, Guldaz HE. Experimental evaluation of cyclic fatigue resistance of four different nickel-titanium instruments after immersion in sodium hypochlorite and/or sterilization. *J Appl Oral Sci.* 2013;21(6):505–10.
223. Plotino G, Grande NM, Mercadé Bellido M, Testarelli L, Gambarini G. Influence of Temperature

- on Cyclic Fatigue Resistance of ProTaper Gold and ProTaper Universal Rotary Files. *J Endod.* 2017;43(2):200–2.
224. Shen Y, Zhou HM, Zheng YF, Campbell L, Peng B, Haapasalo M. Metallurgical characterization of controlled memory wire nickel-titanium rotary instruments. *J Endod.* 2011;37(11):1566–71.
 225. Campbell L, Shen Y, Zhou H, Haapasalo M. Effect of Fatigue on Torsional Failure of Nickel-Titanium Controlled Memory Instruments. *J Endod.* 2014;40(4):562–5.
 226. Alapati SB, Brantley WA, Iijima M, Schricker SR, Nusstein JM, Li UM, et al. Micro-XRD and temperature-modulated DSC investigation of nickel-titanium rotary endodontic instruments. *Dent Mater.* 2009;25(10):1221–9.
 227. Savage NW, Walsh LJ. The use of autoclaves in the dental surgery. *Aust Dent J.* 1995;40(3):197–200.
 228. Viana ACD, Gonzalez BM, Buono VTL, Bahia MGA. Influence of sterilization on mechanical properties and fatigue resistance of nickel-titanium rotary endodontic instruments. *Int Endod J.* 2006;39(9):709–15.
 229. Hilfer PB, Bergeron BE, Mayerchak MJ, Roberts HW, Jeansonne BG. Multiple autoclave cycle effects on cyclic fatigue of nickel-titanium rotary files produced by new manufacturing methods. *J Endod.* 2011;37(1):72–4.
 230. Zinelis S, Darabara M, Takase T, Ogane K, Papadimitriou GD. The effect of thermal treatment on the resistance of nickel-titanium rotary files in cyclic fatigue. *Oral Surgery, Oral Med Oral Pathol Oral Radiol Endodontology.* 2007;103(6):843–7.
 231. Madarati AA, Watts DC, Qualtrough AJE. Factors contributing to the separation of endodontic files. *Br Dent J.* 2008;204(5):241–5.
 232. Velozo C, Silva S, Almeida A, Romeiro K, Vieira B, Dantas H, et al. Shaping ability of XP-endo Shaper and ProTaper Next in long oval-shaped canals: a micro-computed tomography study. *Int Endod J.* 2020;53(7):998–1006.
 233. Gavini G, dos Santos M, Caldeira CL, Machado ME de L, Freire LG, Iglecias EF, et al. Nickel-titanium instruments in endodontics: A concise review of the state of the art. *Braz Oral Res.* 2018;32(suppl.1):44–65.
 234. Adıgüzel M, Capar ID. Comparison of cyclic fatigue resistance of WaveOne and WaveOne Gold small, primary, and large instruments. *J Endod.* 2017;43(4):623–7.
 235. Higuera O, Plotino G, Tocci L, Carrillo G, Gambarini G, Jaramillo DE. Cyclic fatigue resistance of 3 different nickel-titanium reciprocating instruments in artificial canals. *J Endod.* 2015;41(6):913–5.
 236. Ward JR, Parashos P, Messer HH. Evaluation of an ultrasonic technique to remove fractured rotary nickel-titanium endodontic instruments from root canals: Clinical cases. *J Endod.* 2003;29(11):764–7.
 237. Vouzara T, Chares M el, Lyroudia K. Separated Instrument in Endodontics: Frequency, Treatment and Prognosis. *Balk J Dent Med.* 2018;22(3):123–32.
 238. Steven J. Cohen, Gary D. Glassman and RM. Rips , Strips and Broken Tips : Handling the Endodontic Mishap PART I : THE SEPARATED INSTRUMENT. *Oralhealth.* 2005;10–20.
 239. Plotino G, Pameijer CH, Maria Grande N, Somma F. Ultrasonics in Endodontics: A Review of the Literature. *J Endod.* 2007;33(2):81–95.
 240. Terauchi Y, Sexton C, Bakland LK, Bogen G. Factors Affecting the Removal Time of Separated Instruments. *J Endod.* 2021;1–8.
 241. Morgan NB, Painter J, Moffat A. Mean strain effects and microstructural observations during in

- vitro fatigue testing of NiTi. *Proc Int Conf Shape Mem Superelastic Technol.* 2004;79(1):303–10.
242. Braga LC, Magalhães RRS, Nakagawa RKL, Puente CG, Buono VTL, Bahia MGA. Physical and mechanical properties of twisted or ground nickel-titanium instruments. *Int Endod J.* 2013;46(5):458–65.
 243. Rodrigues RCV, Lopes HP, Elias CN, Amaral G, Vieira VTL, De Martin AS. Influence of different manufacturing methods on the cyclic fatigue of rotary nickel-titanium endodontic instruments. *J Endod.* 2011;37(11):1553–7.
 244. Testarelli L, Plotino G, Al-Sudani D, Vincenzi V, Giansiracusa A, Grande NM, et al. Bending properties of a new nickel-titanium alloy with a lower percent by weight of nickel. *J Endod.* 2011;37(9):1293–5.
 245. Lee DH, Park B, Saxena A, Serene TP. Enhanced surface hardness by boron implantation in nitinol alloy. *J Endod.* 1996;22(10):543–6.
 246. Li UM, Iijima M, Endo K, Brantley WA, Alapati SB, Lin CP. Application of plasma immersion ion implantation for surface modification of nickel-titanium rotary instruments. *Dent Mater J.* 2007;26(4):467–73.
 247. Li U-M, Chiang Y-C, Chang W-H, Lu C-M, Chen Y-C, Lai T-M, et al. Study of the effects of thermal nitriding surface modification of nickel titanium rotary instruments on the wear resistance and cutting efficiency. *J Dent Sci.* 2006;1(2):53–8.
 248. Lewinstein I, Grajower R. Root dentin hardness of endodontically treated teeth. *J Endod.* 1981;7(9):421–2.
 249. Liu J. Characterization of new rotary endodontic instruments fabricated from special thermomechanically processed NiTi Wire (Phd Theses). Columbus, Ohio: The Ohio State University; 2009.