UNIVERSIDADE DE SÃO PAULO
FACULDADE DE ODONTOLOGIA DE BAURU

RENAN DIEGO FURLAN

Comparison of mechanical behavior between conventional NiTi, CM, M-Wire and CM-EDM alloy instruments for cyclic fatigue and torsion fracture - Evaluation of fracture surface in Scanning Electron Microscope

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Orientador: Prof. Dr. Clovis Monteiro Bramante

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ABSTRACT

The aim of this study was to evaluate the cyclic and torsional fatigue resistance of Nickel-Titanium rotary instruments manufactured by different thermal treatments. Were tested a total of 140 rotary instruments (n=20): Genius (GN size 25, .04 taper), Trushape (TS size 25, .06 taper), Logic (LOG size 25, .06 taper), Vortex Blue (VB size 25, .06 taper), ProTaper Gold (PTG size 25, .08 taper), Hyflex CM (HCM size 25, .06 taper) and Hyflex EDM (EDM size 25, .08 taper). Cyclic fatigue resistance testing was performed using an artificial stainless steel canal with a curvature (60° angle and 5-mm radius) located at 5 mm from the tip. The files (n=10) rotated until fracture and time was recorded in seconds. The torsional test evaluated the angular deflection and torque at failure of the instruments (n=10) at 3 mm from the tip according to ISO 3630-1. The fractured surface of five instruments of each brand was observed by using scanning electron microscopy (SEM). Data were analysed using one-way ANOVA and Tukey tests, and the level of significance was set at 5%. The cyclic fatigue resistance value of EDM size 25, .08 taper was significantly higher than those of all instruments tested ($P<0.05$). The LOG size 25, .06 taper showed a higher cyclic fatigue resistance than those of GN size 25, .04 taper; TS size 25, .06 taper ($P<0.05$). There was no difference among the others groups. The torsional test showed that PTG size 25, .08 taper had the highest torsional strength value of all instruments tested followed by VB size 25, .06 taper and EDM size 25, .06 taper ($P<0.05$). The LOG size 25, .06 taper showed significant difference only with GN size 25, .04 taper ($P<0.05$). No difference was found among the others groups ($P>0.05$). In relation to angular deflection, the GN size 25, .04 taper; TS size 25, .06 taper; HCM size 25, .06 taper, and EDM size 25, .08 taper showed significantly higher values until fracture than the others groups ($P<0.05$). No difference was found among PTG size 25, .08 taper, LOG size 25, .06 taper, and VB size 25, .06 taper ($P<0.05$). The EDM size 25, .08 taper presented the highest cyclic fatigue resistance among all the tested instruments. For the torsional test, the PTG size 25, .08 taper showed highest torsional strength and lowest angular deflection values.

Keywords: NiTi alloy, rotary motion, torsional fatigue, cyclic fatigue.

RESUMO

O objetivo deste estudo foi avaliar a resistência às fadigas cíclica e torsional de instrumentos rotatórios de Níquel - Titânio fabricados por diferentes tratamentos térmicos. Foram testados o total de 140 instrumentos (n=20): Genius (GN diâmetro 25, conicidade .04), Trushape (TS diâmetro 25, conicidade .06), Logic (LOG diâmetro 25, conicidade .06), Vortex Blue (VB diâmetro 25, conicidade .06), ProTaper Gold (PTG diâmetro 25, conicidade .08), Hyflex CM (HCM diâmetro 25, conicidade .06) e Hyflex EDM (EDM diâmetro 25, conicidade .08). O teste de resistência à fadiga cíclica foi realizado utilizando um canal artificial de aço inoxidável com curvatura (ângulo de 60° e raio de 5mm) localizada a 5 mm da ponta. Os instrumentos (n=10) foram rotacionados até a fratura e tempo foi registrado em segundos. O teste torsional avaliou a deflexão angular e torque até a falha dos instrumentos (n=10) a 3 mm da ponta de acordo com a ISO 3630-1. A superfície da fratura de 5 instrumentos de cada fabricante foi observado utilizando o microscópio eletrônico de varredura (MEV). A análise-estatística foi realizada utilizando o teste de análise de variância com um fator ANOVA e teste de Tukey, o nível de significância foi de 5%. O valor de resistência a fadiga cíclica do EDM diâmetro 25, conicidade .08 foi significantemente maior que todos os instrumentos testados (P<0.05). A LOG diâmetro 25, conicidade .06 mostrou maior resistência à fadiga cíclica que o GN diâmetro 25, conicidade .04; TS diâmetro 25, conicidade .06 (P<0.05). Não houve diferença significante entre os outros grupos. O teste torsional mostrou que PTG diâmetro 25, conicidade .08 obteve o maior valor de torque até a fratura de todos os instrumentos testados seguido por VB diâmetro 25, conicidade .06 e EDM diâmetro 25, conicidade .06 (P<0.05). O LOG diâmetro 25, conicidade .06 mostrou diferença significativa apenas com com GN diâmetro 25, conicidade .04 (P<0.05). Não houve diferença significativa entre os outros grupos (P>0.05). Em relação a deflexão angula, o GN diâmetro 25, conicidade .04; TS diâmetro 25, conicidade .06; HCM diâmetro 25, conicidade .06 e EDM diâmetro 25, conicidade .08 apresentou significantimente o maior valor até a fratura que os outros grupos (P<0.05). Nao foi encontrado diferença significativa entre PTG diâmetro 25, conicidade .08, LOG diâmetro 25, conicidade .06, e VB diâmetro 25, conicidade .06 (P<0.05). O EDM diâmetro 25, conicidade .08 apresentou a maior resistência a

fadiga cíclica entre todos os instrumentos testados. Para o teste torsional, o PTG diâmetro 25, conicidade .08 apresentou o maior valor de torque e menor deflexão angular.

Palavras-chave: liga de NiTi, movimento rotatório, fadiga torisional, fadiga cíclica.

SUMARY

1 INTRODUCTION

1 INTRODUCTION

The endodontic treatment consists in the elimination of the pulpar tissue which suffered damage by bacteria focuses or mechanical trauma, being made by cleaning, modeling and sealing of the root canal system, aiming a maximum disinfection and tapered conical conformation through the cut of dentin, allowing with sealing materials (HULLSMAN et al., 2005).

For many decades the stainless steel was the basic material used in fabrication of the hand files for the practice of endodontics (NEWMAN et al.,1983; WALIA et al. 1988). The stiffness of this metal caused the preparation of curved root canals a challenge making the clinicians adopt methods to circumvent this problem like precurving the instrument (WALIA et al., 1988). Nevertheless, the risks of procedure errors like ledges, transportations, loss of working length and perforations still occurred in a large scale (PONGIONE et al., 2012).

In 1988, Walia et al. brought to the endodontics the Nickel – Titanium (NiTi) alloy, where the authors showed that compared with stainless steel, the NiTi are much more flexible and more resistant to torsional fracture. After this study, a lot of publications became certifying that the NiTi hand files have a better reliance in shaping and maintaining a centrability for curved canals than the stainless steel (PORTO CARVALHO; BONETTI; GAGLIARDI BORGES, 1999; PETTIETTE; DELANO; TROPE, 2001; CHEUNG; LIU, 2009)

The NiTi present very low modulus of elasticity and a wide range for elastic deformation conforming superelastic properties and shape memory (WALIA et al., 1988; THOMPSON, 2000). The superelastic property is the ability of the instrument to suffer large deformation previously to plastic deformation or fracture and the shape memory is the property of the NiTi to deform and recover its original shape (TORRISI, 1999; THOMPSON, 2000). The properties are given to the NiTi because of its structure and phases of the alloy, the Austenite phase is a stable, body-centred cubic lattice, it is an initial phase which is responsible for the shape memory and it can be induced by heating or the absence of tension. The Martensite phase is a closely packed hexagonal lattice, and it can be achieved by cooling down the alloy or applying tension in it, but when the alloy is heated above its transition temperature or the tension is removed, it returns to the Austenite phase (TORRISI, 1999; THOMPSON, 2000). So the effect of shape memory is a consequence of reversible transformation between Austenite and Martensite phases, which does not occur with stainless steel (THOMPSON, 2000).

With the invention of NiTi endodontic instruments, emerged the possibility of use in a continuous rotary motion even in a curved canal (THOMPSON, 2000; HAAPASALO; SHEN, 2013). The root canal preparation with rotary instruments became not only easier and faster but more likely to lead to an improved success rate than preparation with hand instruments (HAAPASALO; SHEN, 2013). The flexibility is beneficial to maintain the original shape of root canal and an adequate torsional and flexural resistance reduces the risk of the instrument failure (THOMPSON, 2000; ZHOUG; PENG; ZHENG, 2013)

John McSpadden designed the first NiTi rotary instrument in a 0.02 taper and came to market in 1992. In 1994, Johnson broke the paradigm of ISO 0.02 tapered instruments and developed what has become known as the ProFile 0.04 tapered series and a while later introduced the Profile 0.06 tapers, the “Orifice Shapers”. Other conventional NiTi rotary files came along afterwards, each with its purported advantages (HAAPASALO; SHEN, 2013). The conventional NiTi alloy are mainly in the Austenite phase in clinical use (body temperature), but when submitted in stress, it past to the Martensite phase, giving place to a more elastic material (TORRISI, 1999). Although, these instruments began to change how dentists viewed instrumentation specially in curved root canals (HULSMANN; PETERS; DUMMER, 2005; PLOTINO et al., 2009; HAAPASALO; SHEN, 2013; SHEN et al., 2013).

Since the introduction of the NiTi alloy in endodontics and its posterior development of the rotary instruments, a lot of researches came to prove a superiority and agility in conclusion of the preparation of curved canals, but in clinical practice, instrument fractures occur in a dynamic mechanism and may result from flexural and torsional stresses (SATTAPAN et al., 2000). Torsional fracture occurs when the tip or any part of the instrument is locked in a canal while the shaft continues to rotate, where the metal exceeds its elastic limit, causing plastic deformation followed by fracture (SATTAPAN et al., 2000). This type of fracture can occur specially in the preparation of narrow and constricted canals, where the file can become stuck and receive a high torsional load (SATTAPAN et al., 2000; WYCOFF; BERZINS, 2012) Torsional failure is characterized by a maximum torsional load and angle of rotation, this property reveals how much the file twist before fracture (ELNAGHY; ELSAKA, 2017). Cyclic fatigue occurs when a metal is subjected in repeated cycles of tension and compression that causes its structure to break down, it happens when the instrument is freely rotated in a curved canal (SATTAPAN et al., 2000; LOPES et al., 2010).

Many factors can affect the torsional strength of endodontic files, such as size, taper, instrument design, metal alloy combination and rigidity, means of manufacturing, flexibility, shape, tips design, (BAHIA; BUONO, 2005) being so, the manufacturers developed different types of design to improve their mechanical properties and clinical performance (PLOTINO et al., 2009; SHEN et al., 2013; ZHOU; PENG; ZHENG, 2013). One of these factors includes defects in surface finishing resulting from the machining process used for manufacturing NiTi endodontic instruments (LOPES et al., 2010; HAAPASALO; SHEN, 2013). The defects are mostly grooves on the surface of the instrument and work as stress concentration factors contributing to fatigue failure (BAHIA; BUONO, 2005; LOPES et al., 2010). Electropolishing is a way the manufacturers made to remove surface defects that might remain after the machining process in attempt to increase resistance to file separation (TRIPI; BONACCORSO; CONDORELLI, 2006; LOPES et al., 2010; SHEN et al., 2013). And the Bio Race was the first rotary system manufactured by electropolishing after grinding process. Some previous studies showed that the surface finishing process minimize the surface grooves upgrading the cyclic fatigue resistance but does not prevent the development of microfractures (RAPISARDA et. al., 2000; HEROLD; JOHNSON; WENCKUS, 2007; SHEN et. al., 2013).

After the introduction of electropolishing, a different approach has been used to optimize the structure of the NiTi alloy (HAAPASALO; SHEN, 2013). A series of thermal treatments and manufacturing were developed with the objective to produce NiTi alloy with substantially stable Martensite phase under clinical conditions (GAO et al., 2012; SHEN et al., 2013). Studies have shown that the thermal treatment increased percentage of Martensite phase (more flexible than Austenite) or R-Phase (transition phase between Austenite and Martensite) giving better physical and mechanical properties compared with instruments manufactured with traditional NiTi alloy (SHEN et al., 2012; SHEN et al., 2013; PLOTINO et al., 2014) The thermal treatment that increase the R-Phase enable the manufacturing of the spiral flutes by twisting process instead of grinding (LOPES et al., 2013; SHEN et al., 2013).

Most of NiTi rotary instruments are manufactured by machining or torsion (LOPES et al. 2013, SHEN et al. 2013, PIRANI et al. 2016, KAVAL et al. 2017). Though, a new rotary system Hyflex EDM (Coltene/Whaledent AG, Altstatten, Switzerland) is manufactured using a noncontact technique of electrical discharge machining (EDM) that can be used to manufacture all types of conductive materials of any hardness with high precision (PEDULLÀ et al., 2016). It consists in a thermal treated blank wire where the EDM induces a melting process and vaporizes the top layer of the NiTi, creating a hard, rough surface, characterized by regularly distributed craters (PEDULLÀ et al., 2016). The authors showed that Hyflex EDM system presented a substantially higher resistance to cyclic fatigue compared with Hyflex CM, which has the same type of thermal treatment (controlled memory wire) and manufactured by machining (PIRANI et al., 2016). It was attributed the responsibility for improvement in its mechanical properties to the EDM manufacturing process (PEDULLÀ et al., 2016; PIRANI et al., 2016)

Presently, there is about six types of thermal treatment used in NiTi instruments: Martensite Wire (M-Wire/2007), R-Phase NiTi(2008), Controlled Memory Wire (CM-Wire/2010)), Blue Wire (2011); Gold Wire (2014) and Max – Wire (2015). (SHEN et al., 2013; PLOTINO et al., 2014; PIRANI et al., 2016; FKG DENTAIRE, 2016; ZUPANC; VAHDAT-PAJOUH; SCHÄFER, 2018) The final goal, is to produce instruments with greater flexibility and increased resistance to cyclic fatigue compared with those constructed from traditional NiTi alloy (SHEN et al., 2013; PLOTINO et al., 2014; KAVAL et al., 2017).

The M-Wire is a modification of 508 Nitinol that has undergone a proprietary method of treatment consisting of machining the blank wire under specific tension and heat treatments at various temperatures, resulting in a material that includes some portion in both the martensitic and the premartensitic R-Phase while maintaining a pseudoelastic state (GAO et al., 2012; PLOTINO et al., 2014). Studies have shown that M-Wire is more resistant to cyclic fatigue test and flexible than conventional NiTi alloy (PEREIRA et al., 2012; SHEN et al., 2013). M-Wire first instrument was introduced by Dentsply, the rotary system denominated Profile GT Series X (Dentsply

Tulsa-Dental Specialties, Tulsa, OK, USA) (SHEN et al., 2013). In 2008, SybronEndo created a new manufacturing process creating the Twisted Files (SybronEndo, Orange, CA) where by the thermal treatment, a raw NiTi wire blank in the austenite phase is transformed into the R-Phase and also its surface is treated by electropolishing (SHEN et al., 2013). The R-Phase is an intermediate phase with a rhombohedral structure between Austenite and Martensite phase, so it allows the manufacturer to twist the file instead of machining it. (LARSEN et al., 2009; SHEN et al., 2013)

In 2010, new Hyflex CM NiTi rotary files (Coltene/Whaledent, Altstästten, Switerzland) with controlled shape memory were introduced. The CM wire is obtained by thermally treating the NiTi wires to shift the Austenite/Martensite transition temperature to a martensitic stable microstructure, so the instrument does not possess “springback action” (SANTOS et al., 2013; PIRANI et al., 2016). This enable the files to be easily bent during use, recovering its original shape by heating above the transformation temperature. (PEDULLÀ et al., 2016; PIRANI et al.,2016). The Hyflex CM is composed by six instruments with double fluted hedstroem design and present four sizes and three tapers: 20 size, 0.04 taper; 20 size, 0.06 taper; 25 size, 0.04; 25 size, 0.08 taper; 30 size, 0.04 taper; 40 size, 0.04 taper. After that, Coltene/Whaledent introduced in market the Hyflex EDM, as explained above, the instrument is derivative by the same thermal treatment of the NiTi alloy (Controlled Memory Wire) but instead of machining is produced with the Electrical Discharge Machining. (PEDULLÀ et al., 2016; PIRANI et al., 2016; GUNDOGAR; OZYUREK, 2017). The Hyflex EDM is presented in size 25 with a constant 0.08 taper in the apical 4mm; the taper decreases to 0.04 toward the coronal region. Throughout the entire working part of the file, there are three different cross sections designs: a quadrangular cross section in the apical region, a trapezoidal cross section in the middle region, and an almost triangular cross section in the coronal region. (PEDULLÀ et al., 2016).

In 2011, Vortex Blue rotary files (Dentsply Tulsa-Dental Specialties, Tulsa, OK, USA) were made available in the market. This system uses a new proprietary method of processing of NiTi wire that results in a distinctive blue color because of a visible titanium oxide layer, this treatment also controls the transition temperatures creating shape memory alloy, studies have shown that it results in superior mechanical properties and performance of the NiTi instruments. (PLOTINO et al., 2014; DUKE et al., 2015; ALCALDE et al., 2017; DE-DEUS et al., 2017). The system Vortex Blue is presented in a pack of six instruments containing a range of size 15 until size 50 and tapers of 0.04 and 0.06 with triangular cross section design. (DENTSPLY SIRONA, 2012)

Protaper Gold (Dentsply Tulsa Dental Specialities) system receive the “Gold” label because of its thermal treatment procedure called Gold treatment (WEBBER, 2015; PLOTINO et al., 2017). The instruments feature identical geometry as ProTaper Universal (Dentsply Tulsa Dental Specialities), presented in 6 instruments with sizes and tapers: size 19, taper 0.04; size 18, 0.02 taper; size 20, 0.04 taper; size 20, 0.07 taper; size 25, 0.08 taper; size 30, 0.09 taper with convex triangular cross section design (HIEAWY et al., 2015). In the Gold thermal process, the NiTi instrument undergoes a heat treatment and slow cooling process that creates Ti_3Ni_4 precipitates dispersed on the NiTi surface (HIEAWY et al., 2015) inducing martensitic transformation to occur in 2 steps and increasing flexibility. (PLOTINO et al., 2017)

In 2015, a novel heat-treated NiTi rotary system, TRUShape 3D Conforming Files (Dentsply Tulsa Dental Specialties, Tulsa, OK) became available in the market. The heat treatment is applied after flutes are ground into blanks from commercially available NiTi to shape the long axis of the file into characteristic bends. (SHEN et al., 2016) It has a characteristic longitudinal S-curve, symmetric triangular cross section, presented in 20, 25, 30 and 40 sizes to a maximum flute diameter of 80 and a 0.06 taper in the apical 2 mm that regresses along the overall length (SHEN et al., 2016; SILVA et al., 2018). The instrument has been claimed to promote greater preservation of dentin during canal shaping, maintaining the integrity of the root structure. (SHEN et al., 2016; SILVA et al., 2018). One year later, in 2016, XP endo shaper (FKG Dentaire, La-Chaux-de-Fonds, Switzerland) consists in a rotary snake-shaped instrument made of a proprietary alloy, the Max-Wire. Because of this new alloy, the file changes its shape according to the temperature (WALID, 2017). When cooled, in its martensitic phase, the file stands straight with a size 30 and an initial taper of 0.01. However, when submitted to body temperature, it changes to its austenitic phase assuming a snake shape that can achieve a final minimum canal preparation of size 30, 0.04 taper when using this instrument alone (WALID, 2017). According to the manufacturer, the XP-endo Shaper instrument applies minimal stress to the dentin walls, adapting easily to canal irregularities. (WALID, 2017; SILVA et al., 2018)

Recently, two rotary systems were launched on the market: the Prodesign Logic (Easy Equipamentos Odontológicos, Belo Horizonte, Brazil) and Genius (Ultradent, Utah, USA) systems. These instruments are manufactured with heat treatment and conventional NiTi alloy, respectively, as reported by the manufacturers. Prodesign Logic system are available in size 25, 0.06 taper; size 30, 0.05 taper; size 35, 0.05 taper; size 40, 0.05 taper, which one with its respective “Glide Path” file (size 25, 0.01 taper; size 30, 0.01 taper; size 35, 0.01 taper; size 40, 0.01 taper). This system presents an S-shaped cross section design for the tapered instruments and a quadrangular cross section for the glide instruments (EASY EQUIPAMENTOS ODONTOLÓGICOS, 2018). Genius system is presented in six files with sizes 25, 30, 35, 40 and 50 with 0.04 tapers and one instrument with size 30, 0.08 taper, all instruments have an S-shaped cross section design (ULTRADENT PRODUCTS, 2016). To the best of our knowledge, there are few studies evaluating the mechanical properties of these instruments.

In short, over the past 2 decades, NiTi instruments have become an important part of the armamentarium for root canal treatment and the files have increased flexibility and strength over the years thanks to all the alloy treatments that have been made (WALID, 2017). Despite their undeniable favorable qualities, unexpected instrument separation might occur, mainly induced by cyclic and torsional fatigue. So it is important to evaluate the mechanical properties of the NiTi rotary instruments to understand their behavior and provide clinicians with reliable recommendations.

The aim of this study was to evaluate the cyclic and torsional fatigue resistance of Genius, Prodesign Logic, Protaper Gold, TRUShape, Vortex Blue, Hyflex CM and Hyflex EDM rotary instruments manufactured by different NiTi alloys. The null hypotheses were that there is no differences in the cyclic fatigue resistance between the instruments and there are no differences in the torsional resistance between the instruments.

2 ARTICLE

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The article that composes this dissertation was drafted according to the publication standards of the Journal of Endodontics.

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Cyclic and torsional fatigue resistance of seven rotary systems manufactured from several NiTi alloys

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Abstract

Introduction: To evaluate the cyclic and torsional fatigue resistance of seven rotary systems Genius (Ultradent, Utah, USA), Trushape (Dentsply Tulsa Dental Especialties, Tulsa, USA), Logic (Easy Equipamentos Odontológicos, Belo Horizonte, Brazil), Vortex Blue (Dentsply Tulsa Dental Especialties, Tulsa, USA), ProTaper Gold (Dentsply Tulsa Dental Especialties, Tulsa, USA), Hyflex CM (Coltene/Whaledent, Altstatten, Switzerland) and Hyflex EDM (Coltene/Whaledent, Altstatten, Switzerland).

Methods: A total of 140 instruments were tested, 20 of each system: Genius (GN size 25/.04), Trushape (TS size 25/.06), Logic (LOG size 25/.06), Vortex Blue (VB size 25/.06), ProTaper Gold (PTG size 25/.08), Hyflex CM (HCM size 25/.06) and Hyflex EDM (EDM size 25/.08). Cyclic fatigue resistance testing was performed using an artificial stainless steel canal with a curvature (60° angle) located at 5 mm from the tip. The files (n=10) rotated until fracture and time was recorded in seconds. The torsional test evaluated the angular deflection and torque at failure of the instruments (n=10) at 3 mm from the tip according to ISO 3630-1. The fractured surface of five instruments of each brand was observed by using scanning electron microscopy (SEM). Data were analysed using one-way ANOVA and Tukey tests, and the level of significance was set at a =5%.

Results: The cyclic fatigue resistance value of EDM 25/.08 was significantly higher than those of all instruments tested (P<0.05). The LOG 25/.06 showed a higher cyclic fatigue resistance than those of GN 25/.04; TS 25/.06 (P<0.05). There was no difference among the others groups. The torsional test showed that PTG 25/.08 had the highest torsional strength value of all instruments tested followed by VB 25/.06 and EDM 25/.06 (P<0.05). The LOG 25/.06 showed significant difference only with GN 25/.04 (P<0.05). No difference was found among the others groups (P>0.05). In relation to angular deflection, the GN 25/.04; TS 25/.06; HCM 25/.06, and EDM 25/.08 showed significantly higher values until fracture than the others groups (P<0.05). No difference was found among PTG 25/.08. LOG 25/.06, and VB 25/.06 (P<0.05).

Conclusions: The EDM 25/.08 presented the highest cyclic fatigue resistance among all the tested instruments. For the torsional test, the PTG 25/.08 showed highest torsional strength and lowest angular deflection values.

Keywords: NiTi alloy, rotary motion, torsional fatigue, cyclic fatigue.

Introduction

Nickel-titanium (NiTi) rotary instruments provide great flexibility and elasticity to perform a safe root canal preparation in curved canal (1-3). However, unexpected instrument separation might occur, mainly induced by cyclic and torsional fatigue (4,5). Cyclic fatigue fracture is caused by the repeated compressive and tensile stresses during instrument rotation in a curved canal (4). Torsional failure occurs when the tip of the instrument is locked in the dentine walls of the root canal and continues to rotate (5). The above-mentioned two types of fatigue might occur simultaneously during root canal preparation of a constricted and curved canal (4,5). Therefore, to minimize this drawback, the manufacturers have considerably changed the instrument designs, alloy processing and manufacturing processes (6-8).

Several heat treatments have been developed to improve the cyclic and torsional fatigue resistance of the NiTi instruments, with the purpose of improving safety during root canal preparation (6,7,9). Usually, the heat treatments change the crystalline disposition of the Nickel and Titanium atoms that undergo the main shift from a cubic (austenitic phase) to a tetragonal molecular arrangement (martensitic phase), inducing different mechanical properties (6-8, 10,11). The high percentage of martensitic phase transformation increases the flexibility and thus, the cyclic fatigue and the deformation capacity during torsional fatigue (6-8, 11). Therefore, the different thermal treatments will provide the NiTi with different mechanical properties (8, 10).

Most of NiTi rotary instruments are manufactured by machining or torsion (2, 7-9). However, the rotary system Hyflex EDM (Coltene/Whaledent AG, Altstatten, Switzerland) is manufactured with the use of an innovative electrical discharger machining (EDM) technique that can shape the NiTi wire by forming an electric potential between the NiTi and the tools (9,11,12). The EDM induces a melting process and vaporizes the top layer of the NiTi, creating a hard, rough, surface (9,11,12). Pirani *et al.* (9) showed that Hyflex EDM files presented a significantly higher cyclic fatigue resistance compared with that of Hyflex CM, which is manufactured by machining and with the same NiTi alloy (controlled memory wire). The authors attributed the responsibility for improvement in its mechanical properties to the EDM manufacturing process.

Currently, several NiTi rotary systems are available in the market, manufactured with different and proprietary heat-treatment and manufacturing processes (6-8) such as: Vortex Blue (Dentsply Tulsa Dental Specialties), TruShape (Dentsply Tulsa Dental Specialties), ProTaper Gold (Dentsply Tulsa Dental Specialties), Hyflex CM (Coltene/Whaledent AG, Altstatten, Switzerland) and Hyflex EDM (Coltene/Whaledent AG, Altstatten, Switzerland). Some previous studies have shown that these instruments have satisfactory mechanical properties, but different mechanical behaviour because of their designs, heat treatments and manufacturing processes (2, 8, 13, 14). Recently, two rotary systems were launched on the market: Logic (Easy Equipamentos Odontológicos, Belo Honrizonte, Brazil) and Genius (Ultradent, Utah, USA) systems. These instruments are manufactured with heat treatment and conventional NiTi alloy, respectively, as reported by the manufacturers. To the best of our knowledge, there are few studies evaluating their mechanical properties up until now.

It is important to assess the mechanical properties of the NiTi rotary instruments to understand their behavior and provide clinicians with reliable recommendations (7, 8,15). Thus, the aim of this study was to compare the cyclic and torsional fatigue resistance of the seven afore mentioned NiTi rotary instruments. The null hypotheses tested were as follows: (1) there are no differences in the cyclic fatigue resistance among the instruments and (2) there are no differences in the torsional resistance among the instruments.

Materials and Methods

A total of 140 NiTi instruments (25 mm length) were selected for this study. The sample calculation was performed using the G*Power v3.1 for Mac (Heinrich Heine, University of Düsseldorf) and by selecting the Wilcoxon– Mann-Whitney test of the *t*-test family. The alpha-type error of 0.05, a beta power of 0.95, and a ratio N2/N1 of 1 were also stipulated. A total of 8 instruments for each group were used as the ideal size for noting significant differences. However, an additional 20% of instruments were used to compensate possible atypical values that might lead to samples loss, thus 10 instruments of each system per test were selected.

For each system, a 0.25 mm tip size intrument was selected, as follows: Genius (GN size 25, .04 taper, TruShape (TS size 25, .06 taper), Logic (LOG size 25, .06 taper), Vortex Blue (VB size 25, .06 taper), ProTaper Gold (PTG size 25, .08 taper), Hyflex CM (HCM size 25, .06 taper), and Hyflex EDM (EDM size 25, .08 taper). All instruments were inspected under a stereomicroscope (Carls Zeiss, LLC, EUA) at 16x magnification before the mechanical test to discard any instruments presenting defects or deformities.

Cyclic fatigue Test

The cyclic fatigue test was performed in a custom-made device that simulated an artificial canal made of stainlles-steel, with a 60^0 angle of curvature and a 5-mm radius of curvature located 5 mm from the tip of the instrument (Fig 1A). The curvature of the artificial canal was fitted onto a cylindrical guide made of the same material (radius, 5 mm). There was an external arch with a 1-mm deep groove that served as a guide path for the instruments, which kept the instruments in the curvature to rotate freely during the test. The device allowed the accurate and reproducible position of the curvature for the all instruments (Fig 1B).

During the cyclic fatigue test, the low-speed handpiece remained in a fixed position, held by brackets bolted to the iron base. This iron base had vertical and horizontal movement to allow the instrument to be inserted into the artificial canal. In addition, there were markings with the angles choiced for the test, thus the iron base could be always fixed in the chosen position and fixed (vertical and horizontal) (Fig 1C).

A total of ten instruments for each rotary system were used, coupled to a VDW Silver Motor (VDW, Munich, Germany) connected to the cyclic fatigue device. The preset programs were selected according the manufactures recommendations:

1. **GN – Genius size 25, .04 taper:** 350 rpm and 0.5N torque.
2. **TS – TruShape size 25, .06 taper:** 300 rpm and 3N torque.
3. **LOG – Logic size 25, .06 taper:** 900 rpm and 4N torque.
4. **VB – Vortex Blue size 25, .06 taper**: 500 rpm and 2.8N torque.
5. **PTG – ProTaper Gold size 25, .08 taper:** 300 rpm and 3.1N torque.
6. **HCM – Hyflex CM size 25, .06 taper:** 500 rpm and 2.5N torque.
7. **EDM – Hyflex EDM size 25, .08 taper:** 500 rpm and 2.5N torque.

During the test, the artificial canal was lubricated with a synthetic oil (Super Oil, Singer Co Ltd, Elizabethport, NJ USA). All the instruments were rotated inside the artificial canal until fracture. The time to fracture was recorded using a digital chronometer. In addition, the number of cycles to failure (NCF) was calculated, according to the rotational speed of the instrument.

Torsional fatigue Test

A total of 10 instruments of each rotary system were tested to measure the torque and maximum angular deflection necessary until fracture. The torsional tests were performed according on the International Organization for Standardization ISO 3630-1 (1992), using a torsional machine as previously decribed (16-18).

The maximum torque and angular rotation were measured, and the ultimate torsional load and angular rotation (^{0}) values were provided by a specifically designed machine (Analógica, Belo Horizonte, MG, Brazil) connected to a computer. The data were recorded by the specific software (MicroTorque, Analógica, Belo Horizonte, MG, Brazil) of the machine. The three millimeters of the instrument tips were clamped into a mandril connected to a geared motor that operated in clockwise rotation, at a speed set to 2 rpm for all the groups.

SEM Evaluation

A total of seventy fractured instruments (n=10 per group) were selected for SEM evaluation (JEOL, JSM-TLLOA, Tokyo, Japan) to determine the topographic features of the fragments after the cylic and torsional fatigue tests. All the instruments were cleaned in a ultrasonic device (Gnatus, Ribeirão Preto, São Paulo, Brazil) using distilled water for 3 minutes after the mechanical tests. The fractured surfaces of the instruments were assessed at 250x magnification after the cyclic fatigue test. In addition, the fractured surface of the instruments used for the torsional test were assessed at 250x and 1000x magnification in the centre of the surface.

Results

Cyclic Fatigue

The mean and standard deviations of time and number of cycles (NCF) to fracture are shown in Table 1. The EDM size 25, .08 taper presented the highest time and NCF values among all instruments ($P<0.05$). The TS size 25, .06 taper showed the lowest time to fracture with a significant difference compared with EDM size 25, .08 taper and HCM size 25, .06 taper ($P<0.05$). In relation the NCF, no difference was found among HCM size 25, .06 taper; LG size 25, .06 taper, and VB size 25, .06 taper ($P>0.05$). The TS size 25, .06 taper showed a significantly lower NCF value in comparison with LG size 25, .06 taper and EDM size 25, .08 taper ($P<0.05$).

Torsional fatigue

The maximum torsional strength and angular deflection values are presented in Table 2. The PTG size 25, .08 taper showed the highest torsional strength in comparison with all the other groups followed by VB size 25, .06 taper ($p<0.05$). The EDM size 25, .08 taper presented a higher torsional load value than HCM size 25, .06 taper, LOG size 25, .06 taper, GN size 25, .04 taper, and TS size 25, .06 taper ($P<0.05$). The LG size 25, .06 taper showed higher torsional values in comparison with HCM size 25, .06 taper, GN size 25, .04 taper, and TS size 25, .06 taper ($P<0.05$). The GN size 25, .04 taper showed the lowest torsional load value with no significant difference compared with HCM size 25, .06 taper.

In relation the angular deflection, the TS size 25, .06 taper, EDM size 25, .08 taper, GN size 25, .04 taper, and HCM size 25, .06 taper presented similar values with no significant difference among them ($P>0.05$). No difference was found among LOG size 25, .06 taper, PTG size 25, .06 taper, and VB size 25, .06 taper ($P>0.05$).

SEM Evaluation

Scanning electron microscopy of the fragment surfaces showed typical features of cyclic fatigue and torsional failure for all instruments tested. In the cyclic fatigue test, all the fractured instrument surfaces showed micro-voids, morphologic characteristics of ductile fracture (Fig. 2). In relation the torsional test, all the instruments showed abrasion marks and fibrous dimples near the centre of rotation (Fig. 2).

Discussion

The mechanical properties of NiTi rotary instruments have been improved during the last decades. The manufacturers have developed NiTi instruments with different tip size, taper, cross-sectional design, core diameter, different thermal treatments of the NiTi and manufacturing processes (3,7-9,15,17). These different features are directly correlated to the mechanical properties and behavior of the NiTi instruments (6-8,17). At present, there are several NiTi rotary systems available and it is important to understand their differences, with the purpose of safety during root canal preparation (12).

In this present study, the static fatigue model was used to ensure the precise position and angle of curvature for all NiTi instruments, irrespective of the taper. Although a dynamic model simulates the clinical pecking motion performed during root canal preparation (15), the static model was used to reduce some variables, such as amplitude of axial motion and speed, which are subjective, because the manually controlled axial motion could be performed in different ways by different clinicians (19). In relation to the torsional test, this was perfomed in accordance with the ISO 3630/1 specification, as in previous studies (16-18). The 3 mm of the tip and instrument shaft were fastened, and clockwise rotation was used for all instruments, because this is the direction of their spiraling flutes (16-18).

The fatigue resistance in the present study was reported both as the time to fracture and as NCF (Table 1). The NCF was calculated because each instrument was used according to the rotational speed recommended by the manufacturers (1,2). The EDM size 25, .08 taper presented the highest time to fracture value in comparison with the values of all the groups ($P<0.05$), and TS size 25, .06 taper showed the lowest time value, with significant difference in comparison with EDM size 25, .08 taper and HCM size 25, .06 taper ($P<0.05$); no difference was found among the other groups ($P>0.05$). Thus, our first null hypothesis was rejected.

Although all the instruments presented same tip sizes (#25), they had different cross-sections, taper, and thermal treatment of NiTi, which affected their mechanical properties (2,8,12,15,20). In agreement with our results, previous studies have shown that EDM size 25, .08 taper had higher cylic fatigue resistance than thermal treated NiTi instruments, such as PTG, HCM, WaveOne Gold, Reciproc Blue (9, 11, 12, 20).

Generally, the thermal treatments of the NiTi improved the cyclic fatigue resistance in comparison with conventional NiTi because they induced a higher percentage of martensitic phase and promoted more flexibility (7,8,12,21,22). However, our results showed that GN size 25, .04 taper presented a longer lifespan than TS ($P<0.05$) and was similar ($P>0.05$) to other heat-treated instruments (HCM size 25, .06 taper; LOG size 25, .06 taper; PTG size 25, .08 taper, VB size 25, .06 taper). A smaller taper and metal mass of the instrument are known to induce better cyclic fatigue resistance (8, 12, 15, 23). Therefore, a possible explanation for these results could be the design features of GN, which presented the smallest taper compared with the other instruments(24). Furthermore, the manufacturing process also plays a role in the fatigue resistance: although EDM size 25, .08 taper and HCM size 25,

.06 taper are manufactured with the same thermal treatment, the eletrectrical discharge machine method is the main factor in the significantly higher cyclic fatigue resistance of this file (9, 11).

The present results were also reported in NCF because of the variation in the rotational speed that are recommend for each instrument. The results shown only in time did not represent the same clinical condition for all instruments when used at different speeds.. According to the present results, EDM size 25, .08 taper also presented the highest NCF value compared with those of all the groups ($P<0.05$) while TS size 25, .06 taper showed significantly lower NCF value in comparison with LOG size 25, .06 taper, and EDM size 25, .08 taper ($P<0.05$). The rotation speed affects the cyclic fatigue because it is related to more repeated compressive and tensile stresses of the NiTi instruments (15, 1, 2). Additionaly, it has been shown that a higher rotation speed increases the NCF value when compared with other instrument used at a lower speed for the same length of time (25). Therefore, the rotation speed recommended by the manufacturer might have affected the cyclic fatigue resistance in this study, because the instruments used at a higher speed were submitted to more mechanical stress in the root curvature. Probably, if the LG size 25, .06 taper, GN size 25, .04 taper, TS size 25, .06 taper, and PTG size 25, .08 taper were used at 500 rpm, as were EDM size 25, .08 taper; HCM size 25, .06 taper and VB size 25, .06 taper; the LG size 25, .06 taper would probably increase the cyclic fatigue resistance, and GN size 25, .04 taper, TS size 25, .06 taper, PTG size 25, .08 taper would present worse results.

The torsional test was performed to evaluate the maximum torsional strength and angular deflection to fracture (5, 16-18, 22). The results of this study, showed that PTG size 25, .08 taper showed the highest torsional strength value in comparison with those of all the other groups followed by VB size 25, .06 taper and EDM size 25, .08 taper ($p<0.05$). The LG size 25, .06 taper showed higher torsional values in comparison with HCM size 25, .06 taper, GN size 25, .04 taper, and TS size 25, .06 taper ($P<0.05$). The GN size 25, .04 taper and HCM size 25, .06 taper presented similar torsional strength values between them ($P>0.05$). In relation the angular deflection, the TS size 25, .06 taper, EDM size 25, .08 taper, GN size 25, .04 taper, and HCM size 25, .06 taper presented similar values with no significant difference among them ($P>0.05$). No difference was found among LOG size 25, .06 taper, PTG size 25, .06 taper, and VB size 25, .06 taper ($P>0.05$). Therefore, the second null hypothesis was rejected.

The heat treatments promoted greater flexibility of the NiTi instruments and in general, favoured a lower torsional load and greater angular deflection (2, 3, 7, 12, 18, 26). However, our results showed that GN size 25, .04 taper presented low torsional load and high angular deflection, such as presented by some heat treated NiTi instruments. Therefore, other variables such as the different cross section design, diameter of core and taper should be considered for this study. Previous reports have indicated that the above-mentioned three factors affected the metal mass volume of the NiTi instruments (5, 7, 8, 27, 28). The larger metal mass tends to promote a higher torsional load and lower angular deflection of the NiTi instruments (9, 12, 27, 29). The different cross-section, diameter of core and taper among them probably promoted a different torsional stress distribuition behavior, affecting the suspectibility to fatigue.

The SEM analysis showed the typical features of cyclic and torsional fatigue for all the instruments. After the cyclic fatigue test, all instruments evaluated showed areas of crack initiation and overload zones, with numerous dimples spread across the fractured surface. After the torsional test the fragments showed concentric abrasion marks and fibrous dimples at the centre of rotation, as previously reported (12, 18, 22, 29).

Clinicians should know about the mechanical properties of NiTi rotary instruments to enable them to use these safely in different clinical situations (8, 12). Among the instruments tested in this study, EDM 25.08 presented the more favourable mechanical properties. The clinical implication of the high angular deflection and suitable torsional strength of the EDM size 25, .08 taper is the possible detection of plastic/permanent deformation signs prior to an eminent instrument fracture because its plastic/permanent deformation may be easily detected (28). In addition, the higher cyclic fatigue resistance could ensure the safe root canal preparation of a severely curved canal.

In conclusion, within the limitations of this study, the EDM size 25, .08 taper presented the highest cyclic fatigue resistance in time and NCF when compared with all the instruments tested. In addition, the PTG size 25, .08 taper showed the highest torsional strength and a low angular deflection.

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The authors declare that they have no conflict of interest.

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Figure Legends

Figure 1 The instrument positioned in the cyclic fatigue test device (A). The artificial canal with an angle 60^0 angle of curvature and radius of 5-mm (B). Markings of the angles choices for the test, which allow to fix the instruments in the same position (C).

Figure 2 Scanning electron microscopy images of fractured surfaces of separated fragments of (A, B, C) Vortex Blue 25.06, (D, E, F) Hyflex EDM 25.08, (G, H, I) Genius 25.04, (J, K, L) ProTaper Gold 25.08, (M, N, O) TruShape 25.06, (P, Q, R) Hyflex CM 25.06, (S, T, U) Logic 25.06 after torsional and cyclic fatigue testing. The first column shows the front view of the instruments at 250X magnification after the cyclic fatigue testing where appears numerous dimples on the fractures surfaces, which constitute a typical feature of ductile fracture; the second column shows the front view images of the instrument at 250X magnification after torsional fatigue testing; the third column shows the concentric abrasion mark at 1000X magnification of the instrument in the second column; the skewed dimples near the centre of rotation are typical features of torsional failure.

FIGURE 1

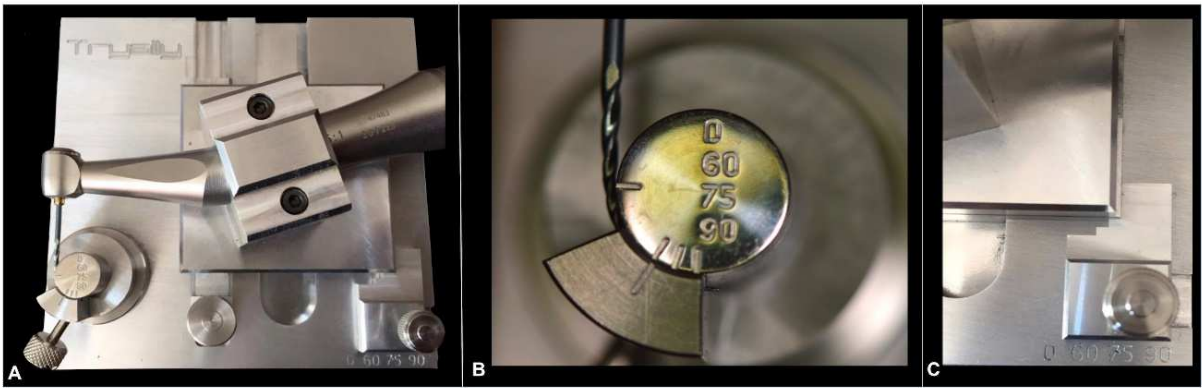

FIGURE 2

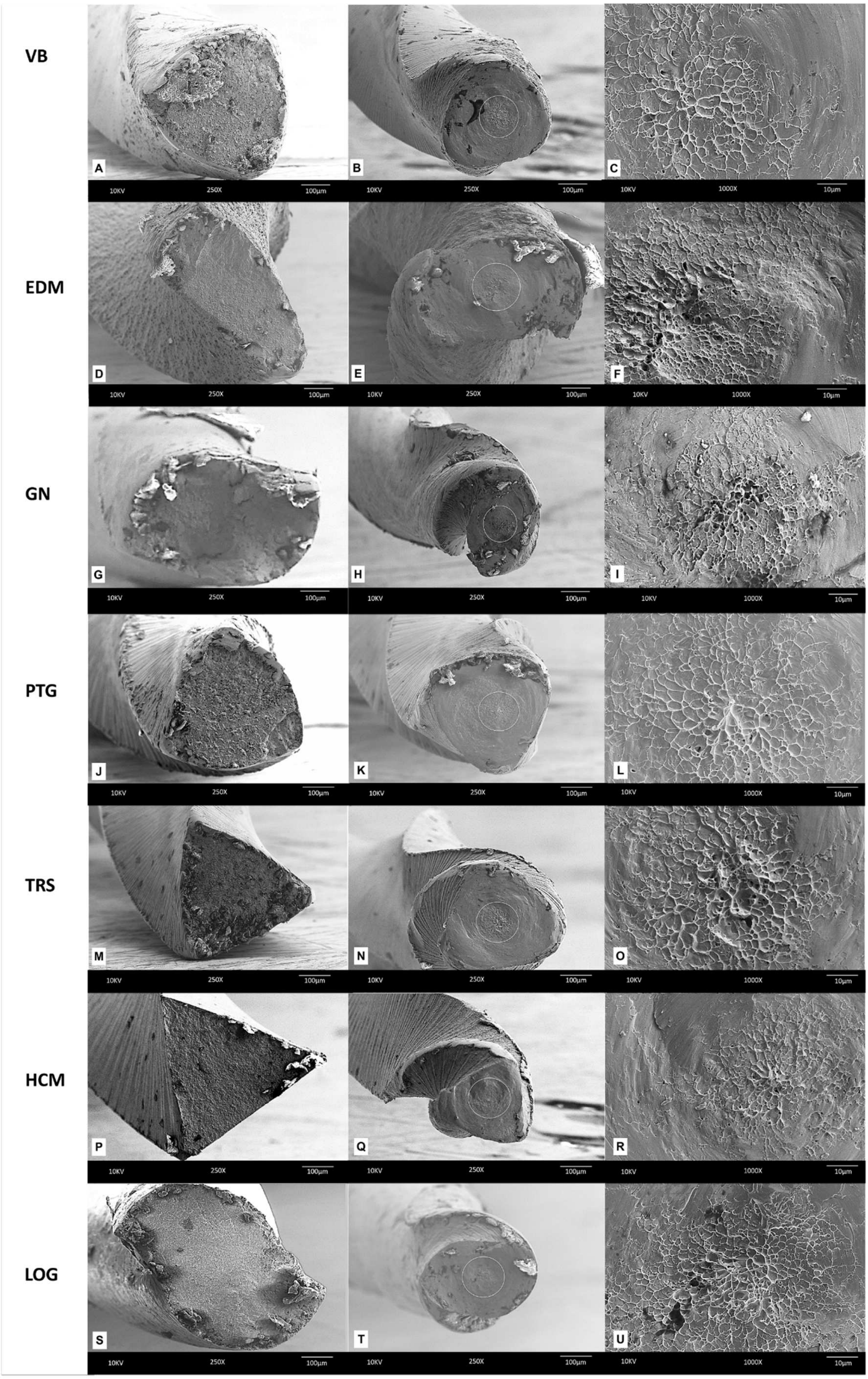
VB
EDM
GN
PTG
TRS
HCM
LOG
A
B
C
D
E
F
G
H
I
J
K
L
M
N
O
P
Q
R
S
T
U
10KV
250X
100μm
1000X
10μm

Table 1. Mean Cyclic Fatigue (time in seconds) and number of cycles (NCF) of instruments tested.

Instruments	Cyclic Fatigue (seconds)		NCF	
	Mean	SD	Mean	SD
EDM 25.08	508.10[a]	93.26	3.867[a]	1.551
HCM 25.06	222.60[b]	31.97	1.623[b,c]	607.9
PTG 25.08	191.00[b,c]	26.97	844[c]	320.7
LG 25.06	197.60[b,c]	36.03	2.238[b]	1.200
GN 25.04	191.40[b,c]	16.38	1.115[c]	95.52
VB 25.06	170.60[b,c]	14.54	1.265[b,c]	458.1
TS 25.06	150.90[c]	21.72	754.4[c]	108.5

SD, standard deviation.
Different superscript letters in the same column indicate statistical differences among groups ($P < .05$).

Table 2. Torque (N.cm) and angular deflection (^{0}) of Instruments tested.

Instruments	Torque (N.cm)		Angles (^{0})	
	Mean	SD	Mean	SD
EDM 25.08	1.17^{c}	0.149	659.70^{a}	82.32
HCM 25.06	$0.66^{e,f}$	0.075	641.50^{a}	53.91
PTG 25.08	1.74^{a}	0.202	323.60^{b}	29.55
LG 25.06	0.90^{d}	0.165	444.10^{b}	73.41
GN 25.04	0.53^{f}	0.084	739.90^{a}	56.97
VB 25.06	1.39^{b}	0.071	393.30^{b}	21.97
TS 25.06	0.72^{e}	0.154	742.30^{a}	193.70

SD, standard deviation.
Different superscript letters in the same column indicate statistical differences among groups ($P < .05$).

3 DISCUSSION

3 DISCUSSION

Since the introduction of NiTi alloy in endodontics, several improvements have been made during the past decades. The manufacturers have developed rotary NiTi instruments with different tip size, taper, cross-sectional design, core diameter, different thermal treatments of the NiTi and manufacturing processes (PLOTINO et al. 2009, ZHOU et al. 2012, SHEN et al. 2013, PEREIRA et al. 2015, PIRANI et al. 2016, KAVAL et al. 2017). These different features are directly correlated to the mechanical properties and behaviour of the NiTi instruments (GAO *et al.* 2012, SHEN *et al.* 2013, PEREIRA *et al.* 2015, KAVAL *et al.* 2017). Despite all different thermal treatments and designs of the instruments, which the aim is a safety root canal preparation, the file separation is a major concern during endodontic instrumentation (LARSEN et al., 2009). At present, there are several NiTi rotary systems available and it is important to understand their differences for suitable and safe clinical use (PEDULLÀ et al*.* 2016). Thus, the aim of this study was to evaluate the mechanical properties of rotary instruments manufactured with different designs and thermal treatments of the NiTi alloy.

In this present study, the static fatigue model was used to ensure the precise position and angle of curvature for all NiTi instruments, irrespective of the taper. The device is a custom-made stainless steel block with simulated artificial canals, with 60^0 angle of curvature and a 5-mm radius of curvature, as previously reported (PLOTINO et al., 2010; DA FROTA et al., 2014). Although a dynamic model simulates the clinical pecking motion performed during root canal preparation (PLOTINO et al. 2009), the static model was used to reduce some variables, such as amplitude of axial motion and speed, which are subjective, because the manually controlled axial motion could be performed in different ways by different clinicians (WAN et al. 2011). In relation to the torsional test, this was perfomed in accordance with the ISO 3630/1 specification, as in previous studies (BAHIA; MELO; BUONO, 2006, PEREIRA et al. 2015, ALCALDE et al. 2017). The 3 mm of the tip and instrument shaft were fastened, and clockwise rotation was used for all instruments, because this is the direction of their spiraling flutes (BAHIA; MELO; BUONO, 2006, PEREIRA et al. 2015, ALCALDE et al. 2017).

The fatigue resistance in the present study was reported both as time and as number of cycles (NCF) to fracture (Table 1). The NCF was calculated because each instrument was used according to the rotational speed recommended by the manufacturers (LOPES et al. 2009, FERREIRA et al. 2017). The EDM size 25, .08 taper presented the highest time to fracture value in comparison with the values of all the groups (P<0.05), and TS size 25, .06 taper showed the lowest time value, with significant difference in comparison with EDM size 25, .08 taper and HCM size 25, .06 taper (P<0.05); no difference was found among the other groups (P>0.05). Thus, our first null hypothesis was rejected.

Although all the instruments presented same tip sizes (#25), they had different cross-sections, core diamenter, taper, and thermal treatment of NiTi, which affected their mechanical properties (PLOTINO et al. 2009, LOPES et al. 2013, PEDULLA et al. 2016, KAVAL et al. 2017, GÜNDOĞAR; ÖZYÜREK, 2017). Also In agreement with our results, previous studies have shown that EDM size 25, .08 taper had higher cylic fatigue resistance than thermal treated NiTi instruments, such as PTG, HCM, WaveOne Gold, Reciproc Blue (PIRANI *et al.* 2016, PEDULLÀ *et al.* 2016, IACONO *et al.* 2017, GÜNDOĞAR; ÖZYÜREK, 2017).

It is likely that different thermal treatments could result in different martensitic phase transformations promoting more flexibility and could induce different dissipations of the energy required for crack formation and propagation during cyclic fatigue test (SHEN et al. 2013, PLOTINO et al. 2014, CHANG et al. 2016, PEDULLÀ et al. 2016, KAVAL et al. 2017). However, our results showed that GN size 25, .04 taper presented a longer lifespan than TS (P<0.05) and was similar (P>0.05) to other heat-treated instruments (HCM size 25, .06 taper; LOG size 25, .06 taper; PTG size 25, .08 taper, VB size 25, .06 taper). A smaller taper and metal mass of the instrument are known to induce better cyclic fatigue resistance (GRANDE et al. 2006, PLOTINO et al. 2009, PEDULLÀ et al. 2016, KAVAL et al. 2017). Therefore, a possible explanation for these results could be the design features of GN, which presented the smallest taper compared with the other instruments. Accordingly to Özyürek *et al.,* who compared GN system with Reciproc Blue and WaveOne Gold in cyclic fatigue, the GN system showed the highest cyclic fatigue resistance and smallest cross-sectional area, but the results cannot be compared with this study because it was made using the reciprocating movement.

Furthermore, the manufacturing process also plays a role in the fatigue resistance: although EDM size 25, .08 taper and HCM size 25, .06 taper are manufactured with the same thermal treatment, the eletrectrical discharge machine method is the main factor in the significantly higher cyclic fatigue resistance of this file (PIRANI et al. 2016, IACONO et al. 2017).

The present results were also reported in NCF because of the variation in the rotational speed that are recommend for each instrument. The results shown only in time did not represent the same clinical condition for all instruments when used at different speeds. According to the present results, EDM size 25, .08 taper also presented the highest NCF value compared with those of all the groups ($P<0.05$) while TS size 25, .06 taper showed significantly lower NCF value in comparison with LOG size 25, .06 taper, and EDM size 25, .08 taper ($P<0.05$). The rotation speed affects the cyclic fatigue because it is related to more repeated compressive and tensile stresses of the NiTi instruments (PLOTINO et al. 2009, LOPES et al. 2009, FERREIRA et al. 2017). Additionaly,It has been shown that a higher rotation speed increases the NCF value when compared with other instrument used at a lower speed for the same length of time (LOPES et al. 2009). Therefore, the rotation speed recommended by the manufacturer might have affected the cyclic fatigue resistance in this study, because the instruments used at a higher speed were submitted to more mechanical stress in the root curvature. Probably, if the LG size 25, .06 taper, GN size 25, .04 taper, TS size 25, .06 taper, and PTG size 25, .08 taper were used at 500 rpm, as were EDM size 25, .08 taper; HCM size 25, .06 taper and VB size 25, .06 taper; the LG size 25, .06 taper would probably increase the cyclic fatigue resistance, and GN size 25, .04 taper, TS size 25, .06 taper, PTG size 25, .08 taper would present worse results.

The torsional test was performed to evaluate the maximum torsional strength and angular deflection to fracture (BAHIA et al. 2006, WYCOFF; BERZINS, 2012, CHANG et al. 2016, PEREIRA et al. 2015, ALCALDE et al. 2017). The results of this study, showed that PTG size 25, .08 taper showed the highest torsional strength value in comparison with those of all the other groups followed by VB size 25, .06 taper and EDM size 25, .08 taper ($p<0.05$). The LG size 25, .06 taper showed higher torsional values in comparison with HCM size 25, .06 taper, GN size 25, .04 taper, and TS size 25, .06 taper ($P<0.05$). The GN size 25, .04 taper and HCM size 25, .06 taper presented similar torsional strength values between them ($P>0.05$). In relation the angular deflection, the TS size 25, .06 taper, EDM size 25, .08 taper, GN size 25, .04 taper, and HCM size 25, .06 taper presented similar values with no significant difference among them (P>0.05). No difference was found among LOG size 25, .06 taper, PTG size 25, .06 taper, and VB size 25, .06 taper (P>0.05). Therefore, the second null hypothesis was rejected.

The heat treatments promoted greater flexibility of the NiTi instruments and in general, favoured a lower torsional load and greater angular deflection (KIM et al. 2009; ZHOU et al. 2012; SHEN et al. 2013; LOPES et al. 2013; PEREIRA et al. 2015; PEDULLA et al. 2016; ALCALDE et al. 2017). However, our results showed that GN size 25, .04 taper presented low torsional load and high angular deflection, such as presented by some heat treated NiTi instruments. Therefore, other variables such as the different cross section design, diameter of core and taper should be considered for this study. Previous reports have indicated that the above-mentioned three factors affected the metal mass volume of the NiTi instruments (BAEK et al. 2011; WYCOFF; BERZINS, 2012; NINAN; BERZINS, 2013; SHEN et al. 2013; KAVAI et al. 2017). The larger metal mass tends to promote a higher torsional load and lower angular deflection of the NiTi instruments (BAEK et al. 2011; KIM et al. 2012; PEDULLA et al. 2016; PIRANI et al. 2016). The different cross-section, diameter of core and taper among them probably promoted a different torsional stress distribuition behaviour, affecting the suspectibility to fatigue.

The SEM analysis showed the typical features of cyclic and torsional fatigue for all the instruments. After the cyclic fatigue test, all instruments evaluated showed areas of crack initiation and overload zones, with numerous dimples spread across the fractured surface. After the torsional test the fragments showed concentric abrasion marks and fibrous dimples at the centre of rotation, as previously reported (KIM et al. 2012; CHANG et al. 2016; PEDULLA et al. 2016; ALCALDE et al. 2017).

Although the studies has been evaluated the cyclic and torsional fatigue resistance in separated tests, it is well known that in clinical use during root canal preparation, the instruments suffer an association of both cyclic and torsional fatigue (SATTAPAN et al., 2000; PEDULLÀ et al., 2016). So, it is important to say that the results should be carefully extended to the clinical conditions (OZYUREK et al., 2017). Therefore, would be important to develop new methodologies that try to reproduce the real mechanical behaviour of the rotary NiTi instruments during its clinical use.

Several factors including operator’s handling, method of use, anatomy of the root canal system, and the dimension of the NiTi rotary file could influence the propensity of the instrument to fracture (PARK et al., 2010). Therefore, clinicians should know and understand about the mechanical properties of the different NiTi rotary instruments to enable them to choose which instrument use safely in different clinical situations (PEDULLA et al. 2016; KAVAL et al. 2017). Among the instruments tested in this study, EDM 25.08 presented the more favourable mechanical properties. The clinical implication of the high angular deflection and suitable torsional strength of the EDM size 25, .08 taper is the possible detection of plastic/permanent deformation signs prior to an eminent instrument fracture because its plastic/permanent deformation may be easily detected (NINAN; BERZINS, 2013). On the other hand, PTG size 25, .08 which exhibited highest torsional resistance, could be more reliable in the treatment of calcified and narrow root canals (KAVAL et al., 2016). In addition, the higher cyclic fatigue resistance could ensure the safe root canal preparation of a severely curved canal.

4 CONCLUSION

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Within the limitations of this study, it can be stated that EDM size 25, .08 taper presented the highest cyclic fatigue resistance in time and NCF when compared with all instruments tested and in addition, the PTG size 25, .08 taper showed the highest torsional strength and a low angular deflection.

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APPENDIX

APPENDIX - DECLARATION OF EXCLUSIVE USE OF THE ARTICLE IN THESIS

We hereby declare that we are aware of the article Cyclic and torsional fatigue resistance of seven rotary systems manufactured from several NITI alloys will be included in the Thesis of the student (Renan Diego Furlan) and may not be used in other works of Graduate Programs at the Bauru School of Dentistry, University of São Paulo.

Bauru, may 22, 2018

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