Evaluation of the Shaping Characteristics of ProTaper Gold, ProTaper NEXT and ProTaper Universal Systems in Curved Canals and the Analysis of Torsional Profiles of New and Used Instruments

by

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Abstract

Shaping characteristics and torsional profiles of the ProTaper Gold system (PTG) were compared with that of ProTaper NEXT (PTN) and ProTaper Universal (PTU) systems. Twenty-four mandibular first molars with 2 separate mesial canals were matched anatomically by micro-CT and prepared with rotary systems (n =16) to F2 or X2 instruments, respectively. Co-registered images were evaluated for 2- and 3-dimensional morphometric measurements. Maximum torque and angle of deflection were determined for 30 new or used PTG, PTN and PTU X2 or F2 instruments. Data was statistically compared using Kruskal-Wallis or Bonferroni/Dunn tests for post hoc and 1-way ANOVA tests (α=5%). PTG and PTN produced less transportation and % decrease in dentin thickness than PTU. PTN had less canal wall contact than PTG and PTU. PTN demonstrated the lowest maximum torque and angle of deflection at fracture and overall mean torque and angle of rotation at fracture decreased after use.
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I. GENERAL INTRODUCTION

1. Apical Periodontitis

1.1 Etiology and Pathogenesis

Apical periodontitis is the term used to describe the inflammatory reaction that ensues as the host mounts an immune response to curtail the spread of microorganisms from the root canal space to the rest of the body. It is caused by bacterial infection and involves pathologic changes of the alveolar bone, periodontal ligament and cementum (Nair 2004). Infection of the pulp tissue in the root canal system constitutes a major etiological factor in the development of apical periodontitis. In the classic study, Kakehashi et al (1966) demonstrated that pulp necrosis and periradicular inflammation developed in rats when their molar pulps were exposed to a conventional oral microflora but no apical periodontitis developed in germ-free rates. Similar results have been replicated in nonhuman primates (Moller et al 1981). Furthermore, when examining traumatized human teeth with intact crowns and necrotic pulps without bacterial contamination, researchers did not report radiographic evidence of periapical bone destruction. However, if bacteria were isolated from traumatized teeth with intact crowns and necrotic pulps, periapical bone destruction was observed (Sundqvist 1976). Apical periodontitis can be caused either by advancement of microbial invaders into the periapical tissues or more commonly their by-products which can egress from the canal space (Sunde et al 2000; Takahashi 1998; Tronstad et al 1987; Pitts et al 1982; Sundqvist and Johansson 1980) . When either is present, the host mounts a complex immunological response that mediates much of the periapical tissue destructions, resulting in the formation of apical periodontitis. Unfortunately, the etiological factors of apical periodontitis within the closed root canal system are, for the most part,
inaccessible to conventional antimicrobial host responses (Nair 2004). Therefore, apical periodontitis is not a self-limiting process and its progression and severity ultimately depend upon a complex interplay between the host response and the invading microbial flora (Stashenko et al 1998).

1.2 Goals of Endodontic Treatment

The goal of endodontic therapy is essentially the treatment or prevention of apical periodontitis (American Association of Endodontics 2012) through effective elimination of the causative agents in the root canal system. Traditionally, this is achieved by disinfection of the canal system using various chemomechanical preparation and irrigation methods (Haapasalo et al 2005), and by prevention of reinfection utilizing a permanent root filling and coronal restoration (Ray and Trope 1995; Saunders and Saunders 1994; Schilder 1974). All methods currently available to clinicians have inherent limitations (Haapasalo et al 2010; Hülsmann et al 2005), necessitating the utilization of multiple techniques in combination. While predictably obtaining a sterile root canal by chemomechanical preparation combined with the use of local disinfection agents in the root canal is not achievable with currently available approaches, this method of combining various techniques has proven more effective in reducing the biomass within the root canal system (Shuping et al 2000; Bystrom and Sundqvist 1985; Byström and Sundqvist 1983; Byström and Sundqvist 1981). This is paramount, as Sjögren et al (1997) demonstrated the importance of obtaining negative cultures for improving the prognosis of the treatment of apical periodontitis. Persistent or recurrent infection of the root canal system post-treatment is mainly attributed to subsequent microbial ingress (Friedman et al 1997), to the resistance of some microorganisms to conventional therapy or inaccessibility due to the complex root canal anatomy (Molander et al 1998; Nair et al 1990).
2. Factors Affecting Intracanal Debridement

2.1 Canal Anatomy

The complexity of the root canal system can not be over-emphasized. Irregularities and aberrations are commonplace, particularly in posterior teeth (Vertucci 1984; Hess and Zurcher 1925). Such aberrations include hills and valleys in canal walls, isthmuses, fins, bifurcations, abrupt curvatures and accessory canals. Conventional radiographs offer a general overview of this complex anatomical system and are essential to the delivery of endodontic treatment (Forsberg 1987), but are unable to provide a true three-dimensional representation of the intricate root canal system (Barton et al 2003; Kaffe et al 1985).

Clearly, our current instrumentation techniques can not remove all microorganisms present in the root canal system (Shuping et al 2000; Bystrom and Sundqvist 1985; Byström and Sundqvist 1983; Byström and Sundqvist 1981) and unfortunately leave approximately 46% of the canal wall surface anatomy untouched (Peters et al 2001). This brings up another important anatomical area for discussion, the dentinal tubules. These anatomical structures are vast, numbering from 15 000 to 45 000 per mm² with a diameter ranging from 2.5 μm to 0.9 μm at the pulp and the dentino-enamel junction, receptively (Garberoglio and Brännström 1976; Nalbandian et al 1960). Enterococcus faecalis has been shown to produce a dense infection of the dentinal tubules, easily reaching 300-400 μm (Haapasalo and Orstavik 1987), while others have found bacteria as well as yeast in the dentinal tubules of extracted teeth as far as 183 μm (Al-nazhan et al 2014). The crevices and nuances of the root canal system that are often inaccessible to conventional chemomechanical techniques (Mandel et al 1990; Langeland et al 1985), and can serve as safe harbors for micro-organisms and the cause of treatment failure.
(Molander et al 1998; Nair et al 1990) and a source of further inflammatory destruction in the periradicular region.

2.2 Chemical Adjuncts

Currently, it is impossible to eradicate intraradicular infection with mechanical instrumentation alone. Therefore, irrigation with antimicrobial agents and inter-appointment medicaments are required to complete contemporary root canal therapy (Sjögren et al 1997).

Various irrigants have been investigated for use in endodontics but sodium hypochlorite is the medicament of choice due to its antimicrobial action and tissue dissolving properties (Estrela et al 2002). Sodium hypochlorite exhibits a dynamic balance, with its antibacterial effect largely dependent on the amount of hypochlorus acid in solution. Its antimicrobial activity is the result of irreversible inactivation of essential bacterial enzymes by hydroxyl ions and chloramination action, while its ability to dissolve organic tissue is the result of saponification reactions (Estrela et al 2002). Controversy regarding the ideal concentration required to achieve effective action during root canal therapy exists, with some suggesting concentrations near 6% (Gomes et al 2001; Waltimo et al 1999), while others recommending lower concentrations of 0.5 – 2.5% (Cvek et al 1976). Clinically, higher concentrations demonstrate greater tissue-dissolution (Hand et al 1978) and with lower concentrations, larger volumes are required to achieve equal results (Moorer and Wesselink 1982). No difference with regards to the antibacterial efficacy of different concentrations of sodium hypochlorite (Siqueira et al 2000; Bystrom and Sundqvist 1985) has been shown, but with lower concentrations frequent exchange is warranted (Senia et al 1971).
Sodium hypochlorite can penetrate dentinal tubules to a depth of up to 300 μm, with penetration depth altered by concentration, time and temperature (Zou et al 2010). While this is clearly a benefit from an antibacterial perspective, it is also a large surface area acted upon by sodium hypochlorite. This may lead to deleterious effects on dentin, such as a reduction in elastic modulus and flexural strength (Mai et al 2010). Indeed, Qian et al (2011) used scanning electron microscopy to examine dentin irrigated with ethylenediaminetetraacetic acid (EDTA) followed by sodium hypochlorite and found that the dentin and dentinal tubule orifices were eroded, irregular and rough with use of 6% sodium hypochlorite. The clinical significance of this is unknown at this time.

While sodium hypochlorite is an effective antibacterial agent, it is also caustic and must be used with great care (Hülsmann et al 2007). Therefore, there is constant research in an effort to find a suitable replacement. Chlorohexidine gluconate (CHX) has been used in dentistry for a long time because of its antimicrobial properties, its substantivity and its low toxicity. It has a wide antimicrobial spectrum and is effective against both Gram-positive and Gram-negative bacteria (Denton 1991). Chlorhexidine gluconate works by electrostatically binding to the charged surface of bacteria and rendering the membrane permeable (Davies 1973) and therefore has no tissue-dissolving capability. Several studies have compared the antibacterial effect of sodium hypochlorite and 2% CHX against intracanal infection and have shown little or no difference between their antimicrobial effectiveness (Buck et al 2001; Vahdaty et al 1993). However, using real-time quantitative-polymerase chain reaction Vianna et al (2006) demonstrated a greater efficacy of 2.5% sodium hypochlorite compared with 2% chlorhexidine gluconate. Importantly though, CHX does not cause erosion of dentin like sodium hypochlorite does as the final rinse after EDTA, and therefore may be a suitable replacement as a final rinse during root canal
therapy (Zamany et al 2003).

During instrumentation a smear layer is formed over the dentin surface (McComb and Smith 1975) and thus hides the orifices of the dentinal tubules. It is composed of mineralized dentin, remnants of pulp tissue, bacteria and biofilm (Pashley 1992). There is a strong consensus on the need to remove it (Haapasalo et al 2005), which can not be accomplished with sodium hypochlorite or chlorohexidine gluconate alone. The addition of a chelating agent such as EDTA to remove the inorganic fraction is required (Goldman et al 1976). EDTA is normally used at a concentration of 17% and 1-2 min (Teixeira et al 2005; Calt and Seper 2002) after sodium hypochlorite is sufficient to remove the smear layer.

There is no single irrigating solution that alone can be considered an optimal irrigant. Optimal irrigation is based on the combined use of 2 or several irrigating solutions, in a specific sequence, to predictably obtain successful treatment outcomes.

**3. Instrumentation of the Root Canal Space**

**3.1 Objectives of Instrumentation**

High quality instrumentation of the root canal is crucial to the prevention or healing of apical periodontitis. Byström and Sundqvist (1981) demonstrated a 2 – 3 log reduction in bacterial counts cultured from infected root canals when instrumented with hand stainless-steel instruments and saline. Similar results were obtained with the use of nickel titanium instruments (Shuping et al 2000). Overall, the aim is to prepare the canal space to facilitate disinfection by
irrigants and medicaments. According to Hülsmann et al (2005), there are seven goals of root canal instrumentation: 1) Removal of vital and necrotic tissue from the main root canal space; 2) Creation of sufficient space for irrigation and medication; 3) Preservation of the integrity and location of the apical anatomy; 4) Avoidance of iatrogenic damage to the canal system and root structure; 5) Facilitation of canal filling; 6) Avoidance of further irritation and/or infection of the periradicular tissues; and 7) Preservation of sound root dentin to allow long-term function of the tooth. Schilder (Schilder 1974) described the need to thoroughly “clean” the root canal system through removal of all organic material within the canal space with instruments and irrigation. He emphasized the need to shape the canal with not only this in mind, but also the technique and material to be used in the final obturation of the canal system.

3.2 Manual Instrumentation

The first described development of an endodontic hand instrument is credited to Edward Maynard in the early 1800s when he notched watch springs to create small needles capable of removing pulp tissue. Later in 1852, Arthur used reamers to enlarge the canal space and it was not until 1915 that the conventional K-type file was introduced by Kerr Dental (Bellizzi and Cruse 1980). Until 1988, hand instruments were constructed from stainless steel (Bellizzi and Cruse 1980) and as the diameter of these instruments increases the inverse is true of their flexibility (Craig et al 1967). This is particularly important in narrow, curved canals. Weine et al (1975) described a number of potential iatrogenic errors, including zipping, ledging, frank perforations and transportation, that can occur during preparation with conventional steel instruments that could impact the healing of apical periodontitis. Various instrumentation techniques have been described in the literature in an attempt to limit iatrogenic damage. One of
the earliest techniques, still widely used in the field of endodontics today, is the step-back technique developed by Clem (1969). This technique involves initial apical enlargement with small diameter instruments followed by progressively larger instruments at reduced lengths of 1 mm. The inverse of this technique was described by Morgan and Montgomery (1984) and involved the initial flaring of the coronal two thirds with Gates-Glidden drills with the objective of removing necrotic debris and limiting straightening of the canal. In the crown-down technique the apical third of the canal is prepared last using successfully smaller diameter instruments to working length. In an attempt to address issues with calcified and severely curved canals Roane et al (1985) described the balanced force technique where instruments were used in a step-down fashion with clockwise and counter clockwise motion.

The literature is equivocal regarding which technique may be superior. The balanced force technique, which is a variant of the classical step-down technique, has been shown to result in less straightening (Calhoun and Montogomery 1988; Sabala et al 1988), while no differences were described when step-back or crown-down techniques were compared together (Luiten et al 1995). However, the crown-down technique has been reported to result in less apical extrusion of debris (Al-Omari and Dummer 1995; Ruiz-Hubard et al 1987). While Roane et al (1985) have described good results with curved canals and only minimal straightening, others have described a high incidence of root perforations (Benenati et al 1986) and instrument fracture (Sabala et al 1988). Nickel titanium instruments were introduced to address the problems associated with rigid stainless steel instruments, and will be discussed in later sections.
3.3 Mechanical Instrumentation

While Gates-Glidden drills were available for use in endodontics in 1885 (Bellizzi and Cruse 1980), the first description of the use of rotary devices was by Oltramare in 1892 where he used needles with a rectangular cross-section in a dental handpiece. Since this time, there have been numerous variations of this concept including reciprocating and rotational devices (Bellizzi and Cruse 1980). Overall, preparation of curved root canals using conventional automated devices with stainless steel instruments resulted in straightening of the main canal (Hülsmann et al 2005). These conventional system also produced significant amounts of debris and smear layer over the root canal wall (Mandel et al 1990) as well as, having issues with perforations and instrument fractures (Friedman et al 1989; Goodman et al 1985). Historically, many of the concerns regarding conventional mechanical instrumentation were likely more a result of the inflexible nature of the instruments being driven, then the mechanism producing the motion.

3.4 Nickel titanium Instruments

Details regarding nickel titanium alloys will be discussed in subsequent sections. With the introduction of instruments constructed from nickel titanium, first described as hand instruments by Walia et al (1988), many of the drawbacks of stainless steel have been overcome and the use of mechanical instrumentation is becoming more widely utilized. When compared to stainless steel instruments, of the same size and geometry, nickel titanium instruments were found to be two to three times more flexible and had a greater resistance to torsional fatigue (Walia et al 1988). Nickel titanium instruments allow for a safer and easier preparation of canals with complex anatomical characteristics (Glossen et al 1995). In a cross-over study designed by
Pettitete et al (2001; 1999), instrumentation by inexperienced dental students using nickel titanium hand instruments resulted in less canal straightening and procedural errors than those instrumented with stainless steel instruments; their results also indicated a better 1-year success rate. Similar findings were found in a retrospective cohort study comparing rotary nickel titanium instruments with stainless steel hand instruments (Cheung and Liu 2009). The authors concluded that there was a 3.8-fold higher chance of success when using rotary nickel titanium instruments compared with hand instrumentation using stainless steel instruments. However, others have found no significant difference (Fleming et al 2010; Iqbal et al 2009; Marending et al 2005).

Neither, nickel titanium or stainless steel and hand or rotary instruments have yielded superior ability to debride the root canal system (Siqueira et al 1999; Dalton et al 1998). Using a novel biofilm model, Lin et al (2013) found no significant difference in the ability of hand and rotary instruments to remove bacteria from the main canal system. Interesting, was the fact that rotary instruments were able to debride biofilm bacteria within an apical groove better than the hand instruments. While others have shown similar results between nickel titanium rotary instruments and stainless steel hand instruments in the coronal and middle thirds, others have found inferior results with rotary instruments in the apical third (Ahlquist et al 2001). Indeed, studies have demonstrated that approximately 30% of the canal wall is not contacted by the rotary instruments during use (Peters et al 2001) which impacts their ability to debride the canal.

While the use of rotary nickel titanium instruments has numerous advantages, major concern regarding the incidence of instrument fractures during root canal preparation exist (Martín et al 2003). The concern with nickel titanium instruments, especially rotary instruments, is the
macroscopic appearance prior to fracture is often unexceptional (Sattapan et al 2000; Pruett et al 1997). Unfortunately, unlike stainless steel that is likely to show signs of unwinding of the flutes prior to catastrophic failure due to plastic deformation, nickel titanium instruments exhibit sudden and catastrophic failure without visual cues (Pruett et al 1997).

4. Materials and Instrument Properties

4.1 Properties of Nickel Titanium Alloys

Nickel titanium (Ni-Ti) alloy was first described by W.F. Buehler in 1963 (Buehler et al 1963) while working for the U.S Navy. The original name was Nitinol (Ni-Ti Naval Ordnance Laboratory). The nickel titanium alloys used in the manufacturing of endodontic instruments are composed of approximately 56% (wt) nickel and 44% (wt) titanium. Some alloys contain approximately 2% cobalt substituted for nickel (Thompson 2000). The result is an equiatomic ratio of the major components, enabling the alloy to exist in multiple crystallographic forms. It is the transformation between austenite to martensite that produces the two features of NiTi that are of relevance to clinical dentistry; these are shape memory and super-elasticity. Austenite is a stable, body-centered cubic, while martensite exists as a close-packed hexagonal lattice (Phillips 1991). In most metals, when an external force exceeds a given amount mechanical slip is induced within the lattice causing permanent deformation; however, with NiTi alloys a stress-induced martensitic transformation occurs, rather than slip. NiTi undergoes phase transformation characterized by small displacements of all the atoms within the structure. The unit cell volumetric change, as austenite transforms to martensite, results in a stress versus effective strain curve giving a low effective elastic modulus. This phenomenon is referred to as
“superelasticity” (Thompson 2000; Phillips 1991). The superelasticity of NiTi allows deformations of as much as 8% strain that is fully recoverable, in comparison with a maximum of less than 1% with other alloys such as stainless steel (Thompson 2000). When the stress decreases or stops without permanent deformation occurring, the martensite reverts back to the parent austenite structure. NiTi is not the only alloy capable of this “superelasticity” phenomenon but it is the most biocompatible and corrosion resistant of this class of alloy (Buehler and Wang 1968). When NiTi is in its martensite phase it is easily bent. When the alloy is heated above a temperature, known as the austenite formation temperature, the alloy returns to its original shape. This is known as “shape memory”, which allows the alloy to return to its previous shape by forming directional and energetic electron bonds that pull back the displaced atoms to their original locations (Thompson 2000).

4.2 Forces Applied During Instrumentation

Rotary NiTi instruments are subjected to flexion and torsion during use in root canal treatment (Zhou et al 2013). NiTi instruments rotating around a curvature for a prolonged period of time are subjected to repeated tensile and compressive stresses such that during each rotation the inner surface of the instrument is compressed and the outer surface is under tension. This results in work hardening within the metal and initiation of cracks leading to eventual cyclic flexural fatigue (Parashos and Messer 2006; Peters 2004). Torsion is a combination of shear, tension and compression that continually alternates direction and magnitude. It occurs when the leading edge of the instrument becomes locked against the canal wall and the shank continues to rotate. The area behind the leading edge is subjected to compressive forces, while the area ahead of the
leading edge experiences mainly tensile forces (Parashos and Messer 2006). Fracture occurs when the elastic limit of the alloy is exceeded.

Examination of the fractured surface using scanning electron microscopy enables the identification of cyclic fatigue fracture that is characterized by numerous patches of linear fatigue striation marks, and torsional failure which is characterized by circular abrasion marks on the fracture surface (Borgula 2005). However, the forces applied to rotary instruments during root canal treatment are complex and instruments often fracture as a result of a combination of flexural fatigue and torsional failure (Gambarini 2001; Sattapan et al 2000).

4.3 Instrument Design Features

Two factors which significantly impact and instruments resistance to fracture when subjected to flexural fatigue and torsional load, are cross-sectional area and file design (Xu et al 2006; Berutti et al 2003). A direct relationship between an instruments diameter and the resistance to torsional failure exists, while an inverse relationship has been demonstrated for flexural fatigue and flexibility (Yared et al 2003; Pruett et al 1997). Berutti et al (2003) examined the impact of cross-sectional design on resistance to fracture by comparing U-flutted ProFile instruments with triangular ProTaper instruments and found a lower and more even stress distribution in the ProTaper instruments. A radial land is a surface that projects axially from the central axis, between flutes, as far as the cutting edge. While landed instruments remain more centered in the canal during use and have a decreased cutting efficiency, it does not appear to impact the resistance to fracture (Cheung and Darvell 2007).
Nickel titanium instruments are often manufactured through machining of a blank wire. This process can leave the surface with grooves and multiple cracks (Valois et al 2005; Alapati et al 2003; Berutti et al 2003) which may act as areas of stress concentration, initiating crack formation during clinical use (Kuhn et al 2001). Indeed, Twisted files have been shown to exhibit increased torsional resistance, flexibility and strength compared to ground files (H. Kim et al 2010; Gambarini et al 2009; Testarelli et al 2009). Interestingly, there is evidence that Twisted files may maintain the original canal anatomy with less canal transportation and better centering ability than ground files (Gergi et al 2015; Al-Manei and Al-Hadlaq 2014), however this remains to be validated. Another method to reduce surface defects is through electropolishing which alters the surface composition of the NiTi instruments, creating a homogeneous oxide layer (Parashos and Messer 2006). Electropolished instruments have been shown to survive a higher number of cycles before fracture than nonelectropolished instruments, but there was no difference in torsional resistance (Lopes et al 2010; Anderson et al 2007).

In recent years, several novel thermomechanical processing and manufacturing technologies have been developed to optimize the microstructure of NiTi alloys. This has resulted in the development of instruments manufactured from M-wire, controlled memory wire and R-phase alloys (Shen et al 2013). M-wire can be formed from transforming raw NiTi wire in the austenite phase into the R-phase through a series of thermal process. The R-phase is an intermediate phase with a rhombohedral structure that can form during forward transformation from martensite to austenite on heating and reverse transformation from austenite to martensite on cooling. It occurs within a very narrow temperature range (Shen et al 2013). CM Wire is a novel NiTi alloy manufactured using a special thermomechanical process that controls the memory of the material, making the files extremely flexible but without the shape memory of
other NiTi instruments, as opposed to what is found with conventional forms of NiTi. Nemours reports have demonstrated that these new NiTi alloys have superior resistance to cyclic fatigue and greater flexibility (Campbell et al 2014; Perex-Higueras et al 2014; Lopes et al 2013; Shen et al 2011; Nguyen et al 2014). This flexibility may explain why instruments manufactured from these alloys are able to maintain the original canal anatomy with minimal canal transportation better when compared with conventional NiTi instruments (Saber et al 2014; Elnaghy and Elsaka 2014; Zhao et al 2014; Zhou et al 2013).

5. Instrumentation Fracture and Canal Transportation

5.1 Causes and Incidence of Instrument Fracture

Numerous studies have attempted to quantify the incidence of instrument fracture by examining clinically discarded instruments or retained fractured instruments (Parashos and Messer 2006). Parashos et al (2004) reported a fracture frequency of 5% from 7 159 discarded rotary NiTi instruments from 14 endodontic practices worldwide. A recent report found a similar rate of 5.1% of 822 rotary NiTi instruments discarded from a graduate endodontic clinic (Alapati et al 2005). Interestingly, Arens et al (2003) reported a fracture incidence of 0.9% of 786 rotary NiTi instruments that had been used once in a specialist endodontic practice. These studies suggest that both operator experience and number of uses may contribute to the incidence of instrument fracture. Indeed, studies comparing general practitioners with endodontic specialists corroborate this (Mandel et al 1999). While multiple clinical uses of rotary NiTi instruments appears to reduce their resistance to cyclic fatigue and torsional fatigue (Fife et al 2004; Yared et al 2003) others have shown that instruments, such as ProTaper Universal which has an incidence of fracture of 2.4%, may be used up to 4 times without any increase in the incidence of fracture.
(Wolcott et al 2006). However, studies do suggest that up to 90% of all NiTi instrument failure are precipitated by repeated use and is accompanied by a decrease in resistance to cyclic fatigue (Stephens and Fuchs 2001). The above studies do not provide information regarding how many of the files remain in the canal or the effect on healing of periapical periodontitis. However, based on the best available clinical evidence it appears the prevalence of retained fractured endodontic hand and NiTi rotary instruments is 1 – 1.6%, respectively (Parashos and Messer 2006).

Sattapan et al (2000) analyzed the type of defects in 378 NiTi rotary instruments after clinical use and observed torsional failure in 55.7% and cyclic fatigue in 44.3% of all instruments. The authors theorized that torsional failure was the result of an excess apical force applied during instrumentation. Canal geometry also plays a significant role in instrument fracture. As the angle of curvature increases and the radius of curvature decreases, the number of cycles to failure decreases (Grande et al 2006; Peters 2004; Zelada et al 2002). A number of other factors may also contribute to the incidence of fracture including instrumentation technique, the use of torque controlled motors, rotational speed, sterilization and instrument design (McGuigan et al 2013).

5.2 Recommendations for Avoiding Instrument Fracture

There are variety instruments currently available to clinicians for use in root canal treatment (Haapasalo and Shen 2013) and while no absolute data exists to establish a specific protocol that will eliminate all procedural errors, some of the factors discussed above can be minimized by widely suggested recommendations (Cheung 2009; Parashos and Messer 2006). First and foremost, adequate training and competency should be achieved in the NiTi system of choice.
before clinical application (Sattapan et al 2000; Mandel et al 1999). As discussed previously, rotary NiTi instruments are at an increased risk of fracture in canals with abrupt curvatures (Peters 2004). Therefore, use of conventional rotary NiTi instruments should be used with extreme caution. However, some of the newer NiTi alloys (M-wire, CM wire, R-phase alloys) are making this less of a concern (Haapasalo and Shen 2013). The use of low-torque controlled motors with NiTi rotary instruments to reduce fracture would seem reasonable, but there is questionable value regarding these devices. For example, Yared and Kulkarni (2004) examined the preset torque values on different commercially available motors and reported that the true torque values were substantially greater than those claimed by the manufacture and that these values exceeded the torsional limit of many rotary NiTi instruments. They also showed no difference in the incidence of fracture between air-driven, high-torque and low-torque motors (Yared et al 2001). Visual inspection under magnification has been suggested by some as a good option to reduce the incidence of fractured instruments by detecting early signs of plastic deformation (Sattapan et al 2000). However, not only do unused instruments exhibit manufacturing defects (Alapati et al 2003) but deformations are often imperceptible (Turpin et al 2000) and Pruett et al (1997) clearly demonstrated that visual inspection for defects was not reliable.

There has been a longstanding discussion regarding single use instruments in endodontics. There has been widespread interest since the recent regulation set forth in 2007, in response to the possible risk of prion transmission, by the department of health in the United Kingdom dictating that all endodontic files must be single use. Manufactures have quickly adopted this strategy. For example, the shank of the WaveOne (Dentsply Maillefer, Ballaigues, Switzerland) rotary NiTi instrument features a plastic sheath that expands after sterilization, preventing reuse. The
literature does not unequivocally support the single use of endodontic rotary NiTi instruments (Parashos et al 2004) and there has never been a confirmed case of prion disease transmission in the dental system to justify the United Kingdom’s stance on the matter (Scully et al 2003). As discussed above, even unused instruments can have significant incidence of fracture as a result of manufacturing defects (Arens et al 2003), and studies have demonstrated that multiple use of instruments can be done without an increase in the incidence of fracture (Wolcott et al 2006; Gambarini 2001; Yared et al 1999). Therefore, it is up to the clinician to adopt a personal policy to prevent excess reuse of rotary instruments, particularly in cases with complex anatomy.

5.3 Effect of Instrument Fracture on Healing

The classic literature, which mostly relates to stainless steel and carbon steel instruments, is equivocal on the impact on outcomes of retained fracture endodontic instruments. Some authors report that retained instruments reduced healing, particularly in the presence of a preoperative periapical radiolucency (Grossman 1969; Strindberg 1956), while others state no impact on healing (Crump and Natkin 1970; Ingle and Glick 1965). A recent retrospective, clinical and radiographic evaluation of 146 fractured instrument cases versus matched controls revealed that the overall success rate of endodontic treatment and retreatment when a fractured NiTi instrument was left within a root canal was not significantly different from that of the controls (Spili et al 2005). Furthermore, the fractured instrument did not compromise the outcome further in the presence of a preoperative periapical lesion; the presence of a preoperative periapical lesion was a more clinically significant prognostic indicator alone. Their findings were corroborated by Ng et al (2011), that reported the presence of a fractured instrument did not
significantly affect the outcome of primary root canal treatment and the same was true of retreatment if patency could be achieved. Finally, Spili et al (2005) suggests that while the presence of a retained fractured instrument does not significantly affect healing, the overall outcome may depend on the stage and remaining microbial load of canal preparation at the time of instrument fracture.

5.4. Canal Transportation

Respecting the objectives of instrumentation when preparing complex canal anatomy can be a challenge (Hülsmann et al 2005). A large number of factors are affected by mechanical root canal instrumentation, including straightening of the canal or transportation, increase in canal area and diameter, and changes in volume (Bürklein and Schäfer 2013). Various procedural errors have been described in the literature associated with canal transportation. These include damage of the apical foramen, elbow formation, zips and perforations (Hulsmann et al 2005; Peters 2004; Weine et al 1975). Root canal anatomy, file design and instrumentation technique may all impact the incidence of root canal transportation. With regards to anatomy, the degree and the radius of canal curvature have a significant impact on the risk of canal straightening (Greene and Krell 1990). The concern with canal transportation in curved canals is that it may lead to an increase in dentin removal along the outer aspect of curve due to the restoring force (Hieawy et al 2015; Pérez-Higueras et al 2014; Pongione et al 2012). A compounding issue is that conventional periapical radiography allows for determination of the curvature in the mesiodistal direction only, while many teeth may also be curved in the beam direction orthogonal to the film (Stropko 1999; Cunningham and Senia 1992).
The combinations of multiple parameters impact an instrument's ability to remain centered in the canal during root canal therapy (Haapasalo and Shen 2013). It is well established that instruments with non-cutting tips result in less canal transportation independent of the alloy used in the manufacturing process (Ponce et al 2003; Dummer et al 1998). In addition to tip design, cross-sectional design and taper of an instrument can impact the amount of transportation in the canal (Bürklein and Schäfer 2013; Schäfer et al 1995). These parameters have a significant effect on the flexibility of the instrument and its ability to negotiate the torturous canal anatomy efficiently. Furthermore, asymmetrical cross-sections can increase the flexibility of an instrument within the canal (Capar et al 2014; Nguyen et al 2014; Bürklein et al 2014) and decrease the stress placed on the instrument (Hieawy et al 2015; Pérez-Higueras et al 2014). These characteristics could impact the ability of the instrument to remain centered in the canal. As discussed in previous sections, the alloy used in the manufacturing process can significantly affect the flexibility and resistance to cyclic fatigue of an instrument (Martín et al 2003); flexibility impacts the amount of transportation because of the reduced tendency of the instrument to straighten within curved canals (Peters and Paque 2010).

Numerous instrumentation techniques have been described in an attempt to maintain the original canal anatomy, decrease operator fatigue and decrease procedural errors. Some of these have been discussed above, however reciprocating motion warrants mention here. Reciprocating motion is based on the balanced-force technique described by Roane (1985). There is evidence that it offers advantages in comparison to continuous rotation; reduced instrument fatigue (De-Deus et al 2010) and better compliance with canal anatomy with lower risk of procedural errors has been reported (Franco et al 2011; You et al 2011). However, many other studies have found the outcomes to be similar between reciprocating and continuous rotation (Berutti et al 2012;
Regardless of the instrumentation technique, file design or metallurgy involved, the question regarding how canal transportation impacts healing of apical periodontitis remains. Surprisingly, few clinical studies exist in the literature regarding the direct impact of canal transportation on outcomes. One clinical trial by Pettiette et al (2001) demonstrated that better maintenance of the original canal shape resulted in increased rates of healing while another clinical study revealed that ledging of root canals resulted in reduced success rates (Cheung and Liu 2009). With the current trend in endodontics today toward conservatism with regards to dentin removal, in an effort to ensure the tooth does not undergo catastrophic failure (Krishan et al 2014) it seems reasonable that maintenance of the original canal anatomy during instrumentation could play a contributing role in this area.

6. Micro-Computed Tomography

6.1 Main Features of Interest

Reliable three-dimensional imaging became a reality in the early 1970s (Hounsfield 1973) with the development of micro-computed tomography (micro-CT) following a decade later (Swain and Xue 2009). Micro-CT uses microfocal spot X-ray sources and high resolution detectors, allowing for projections rotated through multiple viewing directions to produce three-dimensional reconstructed images of samples (Swain and Xue 2009). Computed tomographic images are formed from planar sections through objects and the reconstructed 3D images represent spatial distribution maps of linear attenuation coefficients determined by the energy of
the x-ray source and the atomic composition of the material sampled (Swain and Xue 2009). Nielsen et al (1995) illustrated the tremendous potential of this technology in endodontic research, by using micro-CT with a resolution of 127 μm to show that it was possible to reproduce the canal anatomy accurately and in a nondestructive manner. Since then improvements in micro-CT technology and software have improved the resolution of this imaging modality to 12 μm (Grande et al 2012) with resolution of 5 μm on the horizon (Dowker et al 1997).

6.2 Application in Endodontic Research

Micro-CT analysis has found many useful applications in dental research. It has been utilized in the area of implant and periimplant bone research to examine osseointegration (Park et al 2005), to examine the mineral concentrations of teeth after bleaching (Efeoglu et al 2005) and etching (Peariasamy et al 2001) and the effect of caries (Dowker et al 2003; Gao et al 1993), as well as, to answer research questions concerning tissue engineering (Cartmell et al 2004) and biomechanics (Kim et al 2009). Various researchers have employed micro-CT to study the morphological characteristics of the root canal system, including parameters of surface area, volume, Structure Model Index and canal curvatures (Versiani et al 2013; Versiani et al 2012; Peters et al 2001).

Evaluation of root canal preparation can be a difficult task that is made easier with the high resolution and nondestructive nature of micro-CT (Peters et al 2001a; Peters et al 2001b). The literature contains numerous studies using micro-CT to compare different root canal instruments
(De-Deus et al 2015; Versiani et al 2012; Peters et al 2001) reporting various outcome measures including amount of dentin volume removed, prepared surface area, canal transportation and untouched canal wall. Peters et al (2001a) used micro-CT to compare changes in canal volume and surface area after preparation with four rotary NiTi instrument systems and reported that all instruments left approximately 35% or more of the canal wall surface area untouched. They also concluded that variations in canal geometry before preparation have more influence on the changes during preparation than the techniques and instruments themselves. The information obtained from micro-CT regarding the shaping characteristics of the various instruments allows clinicians make safe and informed decisions regarding which instrument system to use during treatment.

7. Fatigue Testing

It is important that the instruments used for endodontic treatments exhibit mechanical resistance to torsional fracture. Torsional fracture of endodontic instrument can be studied by mechanical tests or clinical use. The two parameters that can be evaluated in mechanical tests include the maximum torque and the angular deflection (angle of rotation) at failure in clockwise rotation. The maximum torque is defined as the maximum torsional strength before failure and the angular deflection as the degrees of rotation along the long axis before failure (Wolcott and Himel 1997). As with the shaping characteristics of an instrument, it is important for clinicians to understand the limitations of the instrument they choose to use for patient treatment.
8. The ProTaper Universal and ProTaper Gold Systems

The ProTaper Universal (PTU; Dentsply Maillefer, Ballaigues, Switzerland) rotary system consists of unique shaping (S1, S2) and finishing (F1, F2, F3, F4, F5) instruments, along with an auxiliary shaping instrument (SX). The S1 and S2 instruments have $D_0$ diameters of 0.17 mm and 0.20 mm with a maximal flute diameter 1.20 mm. The shaping instruments have multiple increasing percentage tapers over the length of their cutting blades (Clauder and Baumann 2004). The unique design allows each instrument to make contact with a specific area of the canal in a “crown down” fashion, focusing on the middle and coronal thirds of the root canal space. In contrary, the finishing instruments exhibit decreasing tapers along their lengths and their focus is on work in the apical third of the canal space (Clauder and Baumann 2004). The F1, F2, F3, F4 and F5 instruments have $D_0$ diameters of 0.20, 0.25, 0.30, 0.40 and 0.50 mm, respectively. All the PTU instruments are manufactured from conventional NiTi, share a similar nonlanded convex triangular cross-section and modified guiding tip with an angle of approximately 39° (Câmara et al 2009). The instruments also have a continuously changing helical angle and pitch over their entire cutting surface that prevents the instrument from screwing into the canal.

The PTU instruments have been extensively studied in the literature. Whipple et al (2009) compared PTU and V-Taper variable rotary systems and found PTU outperformed V-Taper instruments with regards to resistance to cyclic fatigue. Furthermore, mathematical models comparing PTU with Profile rotary files demonstrated lower and greater distribution of stresses along the length of the PTU instruments (Berutti et al 2003). ProTaper rotary instruments have been shown to create more regular canal diameters when compared with FlexMaster, HERO and
Race file systems (Guelzow et al 2005) and maintain the original canal geometry well (Peters 2001). However, PTU instruments have been shown to induce significant amounts of crack formation in dentin (Capar et al 2014) and in comparison to instruments manufactured from new NiTi alloys, PTU exhibits a decreased resistant to cyclic fatigue (Hieawy et al 2015; Pereira et al 2015) and more canal transportation (Celik et al 2013).

Almost no literature exists regarding ProTaper Gold (PTG; Dentsply Maillefer). These instruments have the identical geometry of PTU instruments but are manufactured from a proprietary heat treated NiTi alloy. Hieawy et al (2015) reported that PTG files were significantly more flexible and resistant to fatigue than PTU files which was corroborated by Uygun et al (2015).

9. The ProTaper Next Systems

The ProTaper Next (PTN; Dentsply Maillefer) rotary system has decreased the overall number of instruments and reduced the tip and taper relative to PTU, which may allow for a more conservative apical preparation. The shaper instruments, S1 and S2, have been combined into a single instrument, X1, with D₀ diameter of 0.17 mm and a 0.04 taper. The F1 and F2 instruments have also been replaced by a single instrument, X2, with D₀ diameter of 0.25 mm and a 0.06 taper. The F3, F4 and F5 PTU instruments also have their corresponding counterparts in the PTN instrument system; X3 with D₀ diameter of 0.30 mm and a 0.075 taper, X4 with D₀ diameter of 0.40 mm and a 0.065 taper and X5 with D₀ diameter of 0.50 mm and a 0.06 taper. These instruments are nonlanded and have a noncutting tip similar to PTG and PTU, but the unique characteristics include being manufactured from M-wire alloy and design features include
variable progressive tapers and an off-centered rectangular cross-section (Capar et al 2014). Compared to PTU, the PTN instruments display greater flexibility and resistance to cyclic fatigue (Uygun et al 2015; Pérez-Higuera et al 2014). Multiple researchers have examined the propensity of PTN and PTU to generate dentinal crack formation during use and have found less crack formation with PTN (Capar et al 2014), while others have found no difference (Ustun et al 2015). Studies comparing canal transportation between PTN and PTU report that PTN is able to maintain the original root canal anatomy better than PTU (Saber et al 2014; Uzunoglu and Turk 2015; Wu et al 2015; Elnaghy and Elsaka 2014). Researchers have also examined the amount of apically extruded debris and found less debris extrusion with PTN when compared with PTU (Saliva et al 2015; Capar, et al 2014; Ozu et al 2014). Therefore, it would seem that the unique characteristics of the PTN rotary system have resulted in improvements over the PTU rotary system.
II. OBJECTIVES AND HYPOTHESIS

1. Objectives

The objectives of this *in vitro* study were to characterize the 1) shaping ability and 2) resistance to fracture of ProTaper Gold and compare it with that of ProTaper NEXT and Universal in curved root canals using micro-CT.

The specific aims of the study were to compare ProTaper Gold, ProTaper NEXT and ProTaper Universal systems in extracted human mandibular molars using the following outcome measures:

Part 1

- Ability to remain centered in the root canal during use
- Proportion of canal wall surface untouched by instruments measured by micro-CT
- Amount of remaining dentin thickness in the furcation area after instrumentation

Part 2

- Torsional profiles of new and used instruments

2. Hypothesis

The following null hypotheses were proposed:

(i) There is no significant difference in the shaping characteristics of ProTaper Gold, ProTaper NEXT and ProTaper Universal systems, as assessed with micro-CT.

(ii) There are no significant differences in torsional profiles of ProTaper Gold, ProTaper NEXT and ProTaper Universal systems, new and used instruments.
III. PART 1 – SHAPING CHARACTERIZATION
Evaluation of the Shaping Characteristics of ProTaper Gold, ProTaper NEXT, and ProTaper Universal in Curved Canals

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Abstract

Introduction: This study evaluated the shaping characteristics of the ProTaper Gold system (PTG: Dentsply Maillefer, Ballaigues, Switzerland) and compared it with that of the ProTaper Next (PTN, Dentsply Maillefer) and ProTaper Universal (PTU, Dentsply Maillefer) systems using micro-computed tomographic imaging.

Methods: Twenty-four mandibular first molars with 2 separate mesial canals were matched anatomically using micro-computed tomographic scanning (SkyScan1174v2; Bruker-microCT, Kontich, Belgium) with a voxel size of 19.6 μm. Canals were prepared with PTG, PTU, or PTN rotary systems to F2 or X2 instruments, respectively, and scanned again. Coregistered images were evaluated for 2- and 3-dimensional morphometric measurements of canal transportation, centering ability, untouched canal walls, and remaining dentin thickness. Data were statistically compared using Kruskal-Wallis and 1-way analysis of variance tests (α = 5%). Results: Overall, PTN showed significantly higher percentage values of static voxels than PTG and PTU systems (P < .05). Surface area, perimeter, and minor diameter were higher in the PTG and PTU groups than in the PTN group (P < .05). No difference was observed in form factor, roundness, major diameter, aspect ratio, or structure model index (P > .05). PTG (0.11 ± 0.05 mm) and PTN (0.09 ± 0.05 mm) produced significantly less transportation than PTU (0.14 ± 0.07 mm) (P < .05), and the percentage decrease in dentin thickness was significantly lower for PTG (22.67 ± 2.96) and PTN (17.71 ± 5.93%) (P > .05) than PTU (29.93 ± 6.24%) (P < .05). Conclusions: PTG and PTN produced less transportation and maintained more dentin than PTU. PTN had less canal wall contact than PTG and PTU, but all file systems were able to instrument moderately curved mesial root canals of mandibular molars without clinically significant errors. (J Endod 2015;■:1—7)

Key Words

Canal transportation, micro-computed tomographic imaging, multiple-file system, nickel-titanium instruments, root canal preparation, rotary instruments

Apical periodontitis is caused by root canal infection (1). Its treatment is focused on the elimination of microorganisms by chemomechanical preparation of the root canal (2, 3). Nickel-titanium (NiTi) rotary instruments used for this purpose produce a more centered preparation of the canal, with less transportation than stainless steel instruments (4). NiTi rotary instrument designs continue evolving to optimize their cutting and shaping characteristics. With many new systems available on the market, clinicians require an impartial evaluation of these systems’ characteristics to help them select systems to use clinically.

ProTaper Next (PTN; Dentsply Maillefer, Ballaigues, Switzerland) is a relatively new system. PTN instruments are made of M-wire, a unique NiTi alloy manufactured by a thermal treatment process that reportedly increases flexibility and resistance to cyclic fatigue (5, 6). These instruments incorporate a variable regressive taper design, unique offset mass of rotation, and rectangular cross section, which according to the manufacturer are designed to reduce points of contact with the canal walls generating less fatigue in the instrument during use.

ProTaper Universal (PTU, Dentsply Maillefer) and ProTaper Gold (PTG, Dentsply Maillefer) systems share an identical instrument design with a triangular cross section and a variable progressive taper. PTG is manufactured by proprietary metallurgy that reportedly increases its flexibility and its resistance to cyclic fatigue (7). To our knowledge, research data on the shaping characteristics of PTG were not yet available at the time this study was undertaken. Thus, this study aimed to evaluate the shaping characteristics of the PTG system and compare it with that of the PTN and PTU systems using micro-computed tomographic (micro-CT) imaging.

Material and Methods

Tooth Specimen Selection and Groups

The study protocol was approved by the University of Toronto Research Ethics Board (protocol reference #29482). One hundred fifty permanent mandibular first molars with 2 moderately curved mesial canals (25°–35°) were selected. Teeth were imaged with cone-beam computed tomographic imaging (Kodak 9000; Carestream Dental LLC, Atlanta, GA) set at 66 kV, 10 mA, 10.8-second exposure, and a slice thickness of 76 μm to obtain a pretreatment outline of the root canals. Twenty-four teeth with 2 independent patent mesial canals were selected for further study. These were

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decorated slightly above the cementoenamel junction, disinfected in 0.5% chlorine T solution, and stored in distilled water at 4°C.

Before instrumentation, teeth were mounted on a custom attachment and imaged using a micro-CT system (SkyScan 1710w: Bruker- microCT, Kontich, Belgium) at 50 kV and 800 μA and an isotropic resolution of 19.6 μm. Scanning was performed through 180° rotation around the vertical axis with a rotation step of 1° using a 0.5-mm-thick aluminum filter. The acquired images were reconstructed into cross-sectional slices with NRecon v.1.6.3 software (Bruker-microCT) using standardized parameters for beam hardening (15%), ring artifact correction (5%), and similar contrast limits. The volume of interest was selected extending from the furcation level to the apex of the root, resulting in the acquisition of 700 to 900 transverse cross-sections per tooth in a bitmap (BMP) format. Root canal length, volume, surface area, and dentin thickness from the level of the furcation to the apex of the root were recorded using CTan v.1.14-i software. Sample size calculation indicated that 16 root canals per group were required to support analysis with 80% power and 5% level of significance (8, 9).

Subsequently, 24 mesial roots (48 root canals) were matched to create 8 groups of 3 roots based on the 3-dimensional morphologic aspects of the mesial canals. One root from each group was randomly assigned to 1 of the 3 experimental groups (n = 16) according to the canal preparation systems (ie, PTG, PTU, or PTN). After checking the normality assumption (Shapiro-Wilk test), the degree of homogeneity (baseline) of the 3 groups with respect to canal length, volume, and surface area was confirmed using the 1-way analysis of variance test with a significance level of 5% (α = .05).

Root Canal Preparation

A single experienced operator performed all procedures. Canals were accessed and the coronal third flared with Gates Glidden drills 2 and 3 (Dentsply Maillefer). Apical patency was confirmed with a #10 K-type file (Dentsply Maillefer) passed through the apical foramen before and after canal preparation. The working length (WL) was determined by passing a #10 K-type file through the major foramen and withdrawing it 0.5 mm. A glide path was created using a ProGlider instrument (16/02) (Dentsply Maillefer) carried to the WL. All instruments used were taken to the WL in a continuous clockwise rotation generated by a 6-inch handpiece (Sirona, Bensheim, Germany) powered by an electric motor (VDW Silver Motor; VDW GmbH, Munich, Germany) at 300 rpm and 2.5 Ncm. The instrument sequence in the PTU and PTG groups was S1 (17/02), S2 (20/04), F1 (20/07), and F2 (25/08). In the PTN group, the sequence was X1 (17/04) and X2 (25/06). After gentle in-and-out motion strokes in an apical direction, the instrument was removed from the canal and cleaned. This was repeated until the WL was reached, and then the instrument was discarded. After each step, the canal was irrigated with 20 ml 2.5% NaOCl using a disposable syringe fitted with a 30-G NaviTip needle (Ultradent, South Jordan, UT) placed 1 mm short of the WL. A final rinse with 5 ml 17% EDTA was followed by a 5-ml rinse with distilled water. Canals were dried with paper points (Dentsply Maillefer), imaged with a micro-CT system, and reconstructed with the same parameters used in pretreatment scans.

Outcome Measures

Color-coded 3-dimensional models of the root canals, pre- and post-preparation, were coregistered using automated image registration. Custom combinations of rigid to affine modules were used based on image intensity similarities (3D Slicer 4.3.1 software, available from http://www.slicer.org) with accuracy greater than 1 voxel. Unprepared (green) and prepared (red) matched canals were qualitatively compared using CTan v.2.2.1 software. The area of untouched canal surface was determined by calculating the number of static voxels (vols present in the same position on the canal surface before and after instrumentation). The untouched area was expressed as a percentage of the total number of voxels present on the canal surface (10).

CTan v.1.14-i software was used to measure volume (in mm3), surface area (in mm2), structure model index (SMI), area (in mm2), perimeter (in mm), form factor, roundness, major diameter (in mm), minor diameter (in mm), and aspect ratio of the root canals before and after preparation. Three-dimensional evaluation was performed for the full canal length, and 2-dimensional evaluation was done for the apical 5 mm of the canal in 250 cross-sectional images per canal. Comparison parameters were calculated by subtracting values obtained for treated canals with those obtained from untreated counterparts. Criteria used for the calculation of the parameters have been published previously (10–12).

Canal transportation was assessed from a center of gravity calculated for each slice and connected along the z-axis with a fitted line through a total of 8583 cross sections in the PTU group, 8345 in the PTN group, and 8477 in the PTG group using XLSTAT-3DPlot for Windows (Addinsoft, New York, NY). The mean transportation (mm) was calculated by comparing the centers of gravity before and after treatment for the coronal, middle, and apical thirds of the canals.

The mean percentage decrease of dentin wall thickness was acquired by the superimposition of the data sets before and after canal preparation from the midpoint between the canal orifice and the foramen. Fifteen measurements of the width of dentin toward the distal aspect of the external root surface, perpendicular to a line connecting the centers of gravity, spaced by 1° in either the mesiobuccal or mesiolingual canals were recorded. Color-coded 3-dimensional models of dentin thickness throughout the root were created by CTan v.1.14-i software.

The Shapiro-Wilk test was used to assess the normality of the data. Results of untouched canal wall surface, volume, surface area, SMI, area, perimeter, roundness, form factor, major and minor diameters, and aspect ratio were compared between groups using the Kruskal-Wallis post hoc Dunn test and presented as median values or an interquartile range (IQR). Canal transportation and dentin wall thickness data were normally distributed and compared between groups with the 1-way analysis of variance post hoc Tukey test. Commercially available software (SPSS v.17.0; SPSS Inc, Chicago, IL) was used for analysis at a 5% significance level.

Results

The median and IQR of static voxels indicating an untouched canal surface in each group are shown in Figure 1. A wide range in calculated percentages (0%–34%) was noted among specimens within groups; however, the analysis of the values recorded indicated that for most specimens the variance ranged from 6%–13%. Overall, the PTG group showed significantly higher (P < .05) median percentage values of static voxels (11.66%, IQR = 11.94) when compared with the PTG (3.57%, IQR = 9.92) and PTU (2.66%, IQR = 7.83) groups. No significant difference was noted between PTG and PTU.

The results of the 2- and 3-dimensional analyses are shown in Tables 1 and 2, respectively. Preparation significantly increased all measured parameters in each group. Overall, the percentage increase in the surface area, the perimeter, and the minor diameter of the canals were significantly higher in the PTG and PTU groups than in the PTN group (P < .05). No statistical difference in form factor, roundness, major diameter, aspect ratio, or SMI was present among groups (P > .05). The PTU group produced a significantly larger
increase in canal volume and surface area than the PTG and PTN groups in the coronal and middle thirds of canals \( (P < .05) \), but no significant differences were observed in the apical third. No significant difference in SMI was observed between groups \( (P > .05) \).

Preoperatively, canal cross sections were oval shaped (mean aspect ratio of 1.45), and the canal geometry was irregularly tapered (Fig. 2A). After preparation, the geometry of the canals was larger and showed a smooth taper in all groups (Fig. 2B). Changes in the canal shape, displayed as superimpositions of unprepared (green) and prepared (red) areas, showed that all groups maintained the overall canal shape (Fig. 2C and D).

The results of canal transportation are summarized in Table 3 and graphically represented in Figure 2C and D. The highest transportation values were observed in the middle and apical thirds of the PTU group (~0.50 mm). Overall, the PTN (0.09 ± 0.05 mm) and PTG (0.11 ± 0.05 mm) groups had significantly less \( (P < .05) \) transportation than the PTU group (0.14 ± 0.07 mm).

In the middle third of the root, the mean dentin thickness before preparation was 1.15 ± 0.18 mm, 1.06 ± 0.20 mm, and 1.10 ± 0.32 mm in the PTU, PTN, and PTG groups, respectively. After preparation, dentin thickness ranged from 0.62 to 1.75 mm, 0.72 ± 1.38 mm, and 0.72 to 1.83 mm in the PTU, PTN, and PTG groups, respectively. The percentage decrease in dentin thickness was significantly greater \( (P < .05) \) in the PTU group (29.93% ± 6.24%) compared with the PTN (17.71% ± 5.93%) and PTG (22.67% ± 2.96%) groups. Values for the PTN and PTG groups did not differ significantly \( (P > .05) \). Figure 3 shows a color-coded representation of the dentin thickness throughout the root of a representative specimen from each group. Thick structures are indicated in blue and green, whereas red indicates areas of thin dentin.

### Discussion

Multirooted teeth have complex anatomy and present a greater challenge to successful endodontic therapy than single-rooted teeth. Continued evolution of instruments is intended to facilitate the task. This study evaluated the canal shaping characteristics of the newly introduced PTG system in comparison with those of the widely used PTN and PTU systems using micro-CT imaging, a nondestructive, reproducible, and well-established method for the 3-dimensional assessment of the root canal preparation \( (10–14) \). Unfortunately, the results with the PTG system cannot be compared with others because currently similar studies are not available.

All instruments showed untouched areas of the root canal wall, indicating that none were able to completely clean the dentin walls, which is in agreement with previous studies on Niti rotary systems \( (8, 14–16) \); however, it deserves attention that the mean range of the untouched areas of the root canal wall (6%–13%) were lower than previous reports using similar methodology \( (17, 18) \). It has been shown that variations in canal geometry before instrumentation may have a greater effect on observed changes than the instrumentation.

### Table 3

<table>
<thead>
<tr>
<th>Parameter</th>
<th>PTU</th>
<th>PTN</th>
<th>PTG</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area</td>
<td>0.05 (0.05)</td>
<td>0.05 (0.06)</td>
<td>0.05 (0.07)</td>
</tr>
<tr>
<td>Perimeter</td>
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<td>0.15* (0.10)</td>
<td>0.19* (0.16)</td>
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<tr>
<td>Ratio</td>
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<td>0.84 (0.52)</td>
<td>0.85 (0.70)</td>
</tr>
<tr>
<td>Form factor</td>
<td>1.74* (0.62)</td>
<td>1.48* (0.46)</td>
<td>1.68* (0.63)</td>
</tr>
<tr>
<td>Roundness</td>
<td>0.87 (0.11)</td>
<td>0.87 (0.12)</td>
<td>0.87 (0.16)</td>
</tr>
<tr>
<td>Major diameter</td>
<td>0.88 (0.06)</td>
<td>0.89 (0.05)</td>
<td>0.89 (0.03)</td>
</tr>
<tr>
<td>Minor diameter</td>
<td>0.73 (0.22)</td>
<td>0.67 (0.19)</td>
<td>0.70 (0.27)</td>
</tr>
<tr>
<td>Aspect ratio</td>
<td>0.79 (0.17)</td>
<td>0.82 (0.14)</td>
<td>0.84 (0.13)</td>
</tr>
<tr>
<td>Before preparation</td>
<td>0.31 (0.19)</td>
<td>0.30 (0.16)</td>
<td>0.30 (0.29)</td>
</tr>
<tr>
<td>After preparation</td>
<td>0.58 (0.20)</td>
<td>0.51 (0.16)</td>
<td>0.56 (0.20)</td>
</tr>
</tbody>
</table>

Values in bold letters showing different superscript letters in the same line indicate a statistically significant difference between groups regarding each of the 2-dimensional parameters analyzed (Kruskal-Wallis post hoc Dunn test, \( P < .05 \)).
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Techniques themselves (10). In this way, a less complex pre-operative configuration of the root canals selected in this study may explain the results. Overall, the PTU and PTG systems resulted in significantly less uncut canal walls and a higher increase in the surface area, perimeter, and minor diameter of the canals than the PTN system. These results might be explained by differences in the design of the instruments. Although PTU and PTG share a similar geometry, the smaller dimensions, off-centered mass, and regressive taper of the PTN instruments should reduce the contact area (7) with the canal and, therefore, its cutting ability.

Rotary NiTi instruments have been shown to maintain the original canal curvature well, even in extremely curved canals (19–22). In the current study, movements of the centers of gravity were numerically evaluated in absolute numbers (mm), slice by slice, as canal transportation. Overall, PTG and PTN produced significantly less canal transportation than PTU instruments. Despite PTU and PTG sharing geometric designs, they are manufactured from different alloys, and the more flexible alloy of the PTG, enhanced through a proprietary heat treatment technology, imparts a reduced restoring force (23–25) and may explain why these instruments remained more centered in the canal than PTU during use. This finding is supported by previous studies that compared transportation by M-series systems with those made of conventional NiTi (22, 25). Interestingly, although PTG and PTN share neither geometric design nor metallurgy, the differences did not significantly affect their centering ability. One explanation may be the improved flexibility of the PTN instruments (26) as a consequence of its design feature (off-centered mass of rotation and rectangular cross-section), (wire), and the smaller dimensions of the instrument (25/0.06). The present results are comparable with recent publications on PTN used to prepare curved canals of extracted mandibular first molars (21, 22, 27).

Evaluation of dentin thickness is important because excess removal of dentin could predispose teeth to root fracture (28, 29). Therefore, when an instrument remains centered in the canal, it is expected that more dentin is maintained (30), which may explain the greater percentage of remaining dentin thickness observed with PTG and PTN instruments. PTG and PTN systems also showed similar increases in volume and surface area in the coronal and middle thirds of the root canal despite their different dimensions. It could be hypothesized that heat treatment of the alloy in PTG instruments may predispose the instruments to plastic deformation and disruption of cutting edges during use, reducing their cutting ability. This finding corroborates previous literature that showed plastic deformation of instruments after clinical use as a result of the thermal pretreatment of the alloy (31). However, others have shown that PTN removed similar amounts of dentin as PTU (15).

Interestingly, recent data on cutting efficiency of conventional and non-conventional NiTi instruments showed the “softer” martensitic alloy was the most efficient instrument in lateral action (32). The authors hypothesized that the increased cutting efficiency of Hyles CM1 was related to the alloy’s thermomechanical processing and configuration of the flutes (32); however, in this study, acrylic blocks and bovine dentin were used as substrates, and the findings have not been corroborated by others. It is worth pointing out that, in addition to the prescribed manufacturers’ directions, coronal flaring was performed with Gates Glidden drills. Therefore, changes of the analyzed parameters at this level should be interpreted with caution because they may not represent the efficacy of the preparation systems themselves but also the additional action of the burs. Considering that cutting ability of an endodontic instrument is a result of the complex interrelationship of parameters (15), this assumption warrants further investigation.
Teeth used in this study were anatomically matched in terms of preoperative geometric parameters determined by micro-CT imaging. This procedure creates a reliable baseline and ensures the comparability of the groups by standardization of the 3-dimensional canal morphology in each sample, enhancing internal validity and potentially eliminating significant anatomic biases that may confound the outcomes (10, 16, 33). Although significant differences regarding canal transportation and remaining dentin thickness were obtained, the

**Figure 2.** (A and B) A lateral view of representative 3-dimensional reconstructions of the internal anatomy of mesial roots of a mandibular molar in each experimental group before (green) and after (red) canal preparation. (C) Three-dimensional graphs showing the combination of the preinstrumentation (black line) and postinstrumentation (red line) root canal central axis. (D) Representative cross sections of the superimposed root canals before (green) and after (red) preparation at the coronal (c), middle (m), and apical (a) thirds.

**Table 3.** Mean Transportation (± Standard Deviation) and Range (in mm) of Mesial Root Canals of Mandibular Molars after Preparation with the ProTaper Universal, ProTaper NEXT, and ProTaper Gold Rotary Systems (n = 16 canals)

<table>
<thead>
<tr>
<th>Experimental groups</th>
<th>Coronal third</th>
<th>Middle third</th>
<th>Apical third</th>
<th>All thirds</th>
</tr>
</thead>
<tbody>
<tr>
<td>ProTaper Universal</td>
<td>0.11 ± 0.04&lt;sup&gt;A&lt;/sup&gt; (0.0-0.33)</td>
<td>0.16 ± 0.06&lt;sup&gt;A&lt;/sup&gt; (0.0-0.52)</td>
<td>0.16 ± 0.06&lt;sup&gt;A&lt;/sup&gt; (0.0-0.51)</td>
<td>0.14 ± 0.07&lt;sup&gt;A&lt;/sup&gt; (0.0-0.52)</td>
</tr>
<tr>
<td>ProTaper Next</td>
<td>0.06 ± 0.03&lt;sup&gt;B&lt;/sup&gt; (0.0-0.22)</td>
<td>0.09 ± 0.03&lt;sup&gt;B&lt;/sup&gt; (0.0-0.27)</td>
<td>0.12 ± 0.04&lt;sup&gt;B&lt;/sup&gt; (0.0-0.43)</td>
<td>0.09 ± 0.05&lt;sup&gt;B&lt;/sup&gt; (0.0-0.43)</td>
</tr>
<tr>
<td>ProTaper Gold</td>
<td>0.09 ± 0.04&lt;sup&gt;B&lt;/sup&gt; (0.0-0.33)</td>
<td>0.10 ± 0.05&lt;sup&gt;B&lt;/sup&gt; (0.0-0.30)</td>
<td>0.13 ± 0.05&lt;sup&gt;B&lt;/sup&gt; (0.0-0.39)</td>
<td>0.11 ± 0.05&lt;sup&gt;B&lt;/sup&gt; (0.0-0.39)</td>
</tr>
</tbody>
</table>

Different superscript letters in the same column indicate a statistically significant difference between groups (1-way analysis of variance post hoc Tukey test, P < .05).
**Figure 3.** Dentine thickness throughout the root before and after preparation with different rotary systems. Representative 3-dimensional models of the mesial, distal, and axial cross sections of the mesial roots of mandibular molars are shown. Thick structures are indicated in blue and green, whereas areas of red indicated areas of thin dentin.

clinical relevance of the results obtained remains questionable and may not be clinically significant (30) or affect treatment outcomes. Hence, it is important for clinicians to have impartial information regarding the various characteristics that may affect the shaping characteristics of the PTU, PNS, and PTG systems to facilitate good choices to meet anatomic challenges (24).

**Conclusions**

Within the limitations of this study, PTG and PNS resulted in less transportation and greater ability to maintain dentine thickness than PTU. Differences in measured parameters were small and did not appear to influence the system’s ability to shape moderately curved root canals. Future research should be focused on comparing these systems in severely curved canals and examining PTG with systems manufactured from similar metallurgy.

**Acknowledgments**

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The authors deny any conflicts of interest related to this study.

**References**


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IV. PART 2 – TORSIONAL FATIGUE

1. Methodology

Based on previously published literature using similar methodology, a sample size calculation and power analysis indicated that 30 instruments per group were required for an analysis with 80% power at a 5% level of significance (Lopes et al 2013; Basrani et al 2011; Kell et al 2011). Accordingly, 60 instruments of ProTaper Gold (PTG; Dentsply Maillefer, Ballaigues, Switzerland), ProTaper NEXT (PTN; Dentsply Maillefer) or ProTaper Universal (PTU; Dentsply Maillefer) were allocated equally into group 1, unused instruments or group 2, instruments used to shape two simulated resin canals. All instruments were autoclaved at 134 °C for 3.5 minutes (Stat/ML Cassette Autoclave; SCi Can, Pittsburgh, PA) before use.

Resin blocks (ref. #A 177S, Dentsply Maillefer) were used to simulate canal preparation with the test instruments. The canals were 17-mm long and 0.015 mm in diameter, with a 45° curve at 11 mm and a second 45° curve at 20 mm (Figure 1). Canals were flooded with 2.5% NaOCl before introducing a file into the canal. Working length (WL) was determined by passing #10 K-type file (Dentsply Maillefer) through the apex until it was just seen under loupes with 2.5X magnification and set 0.5 mm short of this point. All instrumentation was performed to this point according to manufactures initial directions for use. Briefly, a glide path was created using a #10 K-type file carried to WL. All instruments used were taken to WL in a continuous clockwise rotation, generated by a 6:1 angle handpiece (Sirona; Bensheim, Germany) powered by an electric motor (VDW Silver motor; VDW GmbH, Munich, Germany) at 300 rpm and 2.5 Ncm. The instrument sequence in the PTG and PTU groups was S1 (17/02), S2 (20/04), F1 (20/07), and F2 (25/08). In the PTN group, the sequence was X1 (17/04) and X2 (25/06). After three
gentle in-and-out motion strokes in an apical direction, the instrument was removed from the canal and cleaned. This was repeated until the WL was reached. Following each step, the canal was irrigated with 5 mL 2.5% NaOCl using a disposable syringe fitted with a 30-G NaviTip needle (Ultradent, South Jordan, UT) placed 1 mm short of the WL. All instruments were used to instrument two resin blocks.

The testing equipment was composed of a computer controlled reversible geared motor (Smart Motor; Shelley Automation, Cambridge, Ontario) that rotated a test file by means of a separated hardened steel chuck (Figure 2). The handle of each file was removed with a suitable wire cutter at the point where the handle was attached to the file shaft. The file shaft was set in the steel chuck of the motor that was connected by way of plastic gears to a contactless rotary sensor (SRH 280P; Durham Instruments, Toronto). The motor could move freely in the horizontal direction on bearings in a track. The file tip was placed in the jaws of a soft brass chuck attached to a torque-sensing device (Model RTS-50; Transducer Techniques, Temecula, CA). The electrical signal from the load cell and rotary sensor were amplified (Type S7DC RDP Electronics Ltd, UK) and digitized at 10 Hz. Data acquisition was achieved using EspressoDAQ module (DQ401; HBM, Germany) and catman Easy software (HBM, Germany).

Each file was gripped by the chuck attached to the torque sensing device at 3 mm from its tip. A jig was used that allowed the precise measurement of the 3 mm mark for each file. The motor was programmed to rotate at a constant 2 RPM for 1780 degrees (or 5 revolutions) in a clockwise direction. The main outcome measures were maximum torque
(Ncm) and angle of rotation (°) at fracture. The maximum torque value was determined as the average of five data points immediately before a sudden drop to zero. After normality conditions were verified, data were contrasted using one-way analysis of variance with Bonferroni/Dunn tests for post hoc comparisons (SPSS v17.0 software; SPSS Inc., Chicago, IL). The alpha-type error was set at 0.05. Randomly selected fractured instruments from each group were examined by scanning electron microscopy (Hitachi S-570; Tokyo, Japan) at 200 and 1000 X magnification.

2. Results

Typical torque curves (Fig. 3-5) showed a rapidly increasing phase followed by little or no yielding and a sudden drop at fracture. Occasionally, a point of maximum torque was recorded before instrument fracture, but in other cases the maximum torque coincided with the fracture. Means and standard deviation values of torque and angle of rotation at fracture of the two groups for PTG, PTN and PTU are shown in Table 1. PTN had the lowest mean torque at fracture and was statistically significant (P < .05) for either new or used instruments. Maximum torque at fracture significantly (P < .05) decreased for PTG and PTU while an increase was recorded for PTN between new and used instruments. The angle at fracture differed significantly between PTG, PTN and PTG when new instruments were tested (P < .05, Table 1), however only PTG had a significantly lower mean angle after use. The scanning electron microscopic topographic appearance of the fracture surfaces of PTG, PTN and PTU showed typical features of torsional failure, including characterized by circular abrasion marks and skewed dimples near the center of rotation (Fig. 6-8).
V. DISCUSSION

1. Part 1 – Shaping Characteristics

A major source of bias in the study was the use of Gates Gladden drills to preflare the orifices prior to instrumentation. However, the creation of straight-line access, by convention, is important prior to use of NiTi rotary driven instruments into the canal. Failure to do so can lead to repeated cycles of bending, and ultimately cyclic fatigue (Lopes 2013; Leeb 1983). The first step in this process is flaring of orifices to remove restrictive dentin. A variety of techniques are available to accomplish this. One such instrument, the Gates-Glidden drills are still widely used and are an economical and efficient method to accomplish this goal. As the thickness of remaining dentin could be profoundly affected by the use of these instruments, evaluation of the dentin thickness was performed in the middle third of the root instead of the coronal third in order to observe the pure effect of the preparation systems. However, changes of the analyzed parameters should still be interpreted with caution because they may not represent the efficacy of the preparation systems themselves, but also the additional action of the burs.

Just as preflaring of the canal orifices prior to the introduction of NiTi rotary driven instruments into the canal is important, so is the creation of a glide path. Most manufactures recommend the use of a glide path prior to the introduction of NiTi rotary instruments. The creation of a glide path of the canal has been reported to allow the preservation of a pathway to the full working length, thus avoiding excessive binding in the canal. Berutti et al. (2014) demonstrated the ability of ProGlider to reduce stress in PTN X1 instruments during shaping through the
generation of a glide path. Indeed, researchers have demonstrated a lower incidence of fracture of NiTi rotary instruments when a glide path is present (Pation et al 2005). Interestingly, PTN instruments revealed better performance and fewer canal aberrations when a glide path was created before instrumentation (Elnaghy and Shaymaa 2014).

2. Part 2 – Torsional Fracture

While the simple presence of a fractured instrument does not appear to affect the outcome of endodontic treatment (Spili et al 2005), it is preferable to minimize its occurrence in a clinical scenario. Knowledge regarding how new instrument designs affect the resistance to fracture is useful to enable clinicians to make decisions regarding which instrument system to utilize. Furthermore, multiple use of instruments has been related to a decrease in resistant to fracture (Yared et al 2003; Plotino et al 2006). Therefore, the torsional profile of PTG was determined for new and used instruments and compared to PTN and PTU instruments.

Initial sample size was based on literature utilizing similar methodology to determine torsional fracture. A sample size calculation was performed and 30 instruments per group were required for analysis of 80% power and 5% significance. This appears to be in agreement with others, as Basrani et al (2011) and Kell et al (2009) used a very similar test setup with 30 instruments per group to determine the torsional profiles of new and used Revo-S and GT instruments. A pilot study was conducted to calibrate the primary investigator (JG) with regards to the instrumentation procedures (apical pressure, irrigation, recapitulation and visual inspection with magnification). Six resin blocks were used per instrument group over two different days. There
was noticeable difference between the “shape” of the canal in the resin blocks between the two days. Therefore, all instrumentations procedures for the PTG, PTN and PTU groups were performed on the same day to minimize this variation. All attempts were made to simulate a clinical situation through the development of a glide path, the use of sodium hypochlorite (2.5%) and sterilization of instruments between uses. Some studies suggest that multiple sterilization cycles may produce crack initiation and propagation, with an increase in depth of surface irregularities (Valois et al 2005; Rapisarda et al 1999; Mize et al 1998). However, recent studies conducted by Plotino et al (2012) and Hilfer et al (2011) found no difference with most of the instruments tested, even after 10 sterilization cycles. Furthermore, while sodium hypochlorite has the potential to increase corrosion and micropitting of NiTi alloy (Sarkar et al 1983), a recent study examining the cyclic fatigue resistant of NiTi instruments after immersion in 2.5% sodium hypochlorite concluded that NiTi instruments were not adversely affected by sodium hypochlorite immersion even after 5 cycles of autoclave sterilization (Bulem et al 2013).

Resin blocks were used to simulate root canals because they allow standardization of degree, location and radius of curvature (Fig. 1), as well as canal length, width and hardness that is not possible with human roots. Microhardness of dentin has been measured as 35-40 kg/mm² near the pulp space, while the microhardness of resin is in the range of 20-22 kg/mm² (Kell et al 2009; Lim and Weber 1985). Considering that the hardness of resin is approximately 50% that of dentin, instrumentation of 2 resin blocks was used to simulate clinical use during root canal therapy of a single canal. However, it must be emphasized that resin and dentin do not behave the same under clinical situations; the size of resin chips and natural dentin chips are not identical and blockage is frequent and debris removal more difficult with resin (Lim and Weber
Therefore, the results of this study should be interpreted with caution as they my not be transferrable to the clinical situation.

Determination of the torsional profiles of PTG, PTN and PTU instruments followed ANSI/ADA Specification No. 28 for testing endodontic hand instruments which provides guidelines for “twisting”, “bending” and “pulling” mechanical tests. While developed for testing of hand instruments and reamers, it is ubiquitously utilized in the endodontic literature and therefore allows for comparison with studies on other instruments. The specification involves rotating an instrument around its long axis with its tip bound until fracture and provides information regarding torque and angle of rotation at fracture. This is a static test and does not provide information regarding fatigue failures. Therefore, this method of testing has created controversy (Sattapan et al 2000). However, torsion has been shown to account for 55.7% of the failures of NiTi rotary instruments (Alapati et al 2005; Sattapan et al 2000) and ANSI/ADA Specification No. 28 was deemed appropriate for testing of torque using engine driven endodontic instruments and to simulate the clinical scenario of the instrument tip binding within the canal (Sattapan et al 2000). While manufacturers of PTG, PTN and PTU instruments recommend torque controlled motors to operate at 300 rpm, testing in this method is performed at 2 rpm to minimize the affect on the outcome variables (Karagöz-Küçükay et al 2003; Zelada et al 2002).

Significant differences in torque at fracture were observed between new and used instruments; mean torque of PTG and PTU decreased while PTN increased after use. The values for torque obtained in this study were comparable with those for PTU and PTN reported by other researchers (Pereira et al 2015; Hussne et al 2011; Vieira et al 2009), unfortunately no data currently exists regarding PTG to compare with. During clinical use, NiTi instruments are
subjected to cyclic fatigue and torsional load that contribute to instrument fracture (Gambarini 2001). In this study, instruments were pre-stressed in resin blocks with S-shaped canals that would produce cyclic fatigue in the instruments. Ulmann and Peters (2005) found that cyclic pre-stressing significantly reduced torsional resistant of ProTaper finishing files and it has been reported instruments cycled to 75% of their fatigue life have a significant decrease in torsional resistance (Shen et al 2011). The increased mean torque after use of PTN may be explained by work hardening as a result of instrument stress during use. A similar result was reported by Kell et al (2009) that examined the torsional profiles of new and used GTX rotary instruments; they speculated that this increase may occur because some of the R-phases and martensite phases may have been permanently transformed to the austenite phase during initial use of the instrument and the observed result a consequence of the mechanical properties of austenite phase being much higher than that of martensiste or R-phases. Furthermore, while PTG and PTU share a similar geometry, PTN is manufactured with an off-centered rectangular cross-section that might enhance the torsional resistance of the instrument (Pereira et al 2013). Indeed, such a modification in the cross-section should result in a reduction of the contact area with the canal and therefore its torsional loads (Blum et al 1999). However, in our study PTN had the lowest mean torque at fracture and as might be expected based on the similar geometry, no significant differences were observed between PTG and PTU instruments, either new or used. Interestingly, Gao et al (2012) compared M-Wire and Vortex Blue, similar to PTG in alloy properties, and showed that the Vortex Blue had approximately 20% higher torque strength compared to M-wire. It has been reported that increasing the core diameter of an instrument is related to an increase in torsional resistance (Wycoff and Berzins 2012) and therefore our results may seem contradictory. However, this may not be the case because the apical taper of the PTG and PTU instruments
tested is 0.08 while that of the PTN instrument is 0.06. Therefore, the central core is significantly smaller in the PTN instruments and may explain our results.

Significant differences in mean angle at fracture were observed between new PTG, PTN and PTU instruments; the largest mean angles were recorded for PTG (238.36 ± 39.46 °) and PTU (203.59 ± 51.55 °). While these instruments have similar core mass and geometry, which is likely a significant contributing factor, PTG is manufactured from a proprietary heat treated alloy that has been reported to increase the instruments flexibility and resistance to cyclic fatigue (Hieawy et al 2015). The results of this study are in agreement with other studies that reported instruments manufactured from shape memory alloy presented a high angle of rotation before fracture (Pereira et al 2015; Ninan and Berzins 2013). This may be associated with additional deformation provided by the reorientation of martensite (Santos et al 2013). The lower mean angle of fracture of PTN may be a result of the unique rectangular cross-section and smaller taper. Overall, there was a decrease in the angle of fracture for the used instruments, however, only PTG was significant. These results confirm those of other studies that compared a variety of new and used NiTi rotary instruments (Vieira et al 2009; Kell et al 2009). However, the importance of the angle at fracture is controversial because at the typical rotational speed of 300 rpm, differences in the angle at fracture occur in one-fifth of a second and therefore it is unlikely to be perceived during clinical use (Vieira et al 2009). Still some authors believe that angle at fracture acts as a safety factor because the instrument can undergo higher elastic and plastic deformation before fracture (Lopes et al 2011; Seto et al 1990; J. Wolcott and Himel 1997).
SEM analysis of the fracture cross-sections of new and used PTG, PTN and PTU showed similar surface features of torsional fracture including skewed dimples near the center of the fracture surface and circular abrasion streaks (Barbosa et al 2008; Alapati et al 2005).
VI. CONCLUSION

The overall results of this study indicate it is appropriate to reject the null hypothesis and accept the alternate hypothesis. Within the limitations of this *in vitro* study, PTG and PTN resulted in less transportation and greater ability to maintain dentin thickness than PTU. Differences in measured parameters were small and did not appear to influence the systems ability to shape moderately curved root canals. PTN, manufactured from M-wire alloy, has the lowest mean torque and angle of rotation at fracture when compared to PTG and PTU. The recurring use of PTG, PTN and PTU rotary instruments produced significant differences in torque at fracture and a significant smaller angle of rotation at fracture was observed for PTG. Future research should be focused on comparing these systems in severely curved canals and in examining PTG with systems manufactured from similar metallurgy.
VII. REFERENCES


VIII. TABLES AND FIGURES

1. Tables

Table 1. Mean (and standard deviation) torque and angle at fracture for ProTaper Gold, ProTaper Next or ProTaper Universal instruments tested unused or after use to instrument two simulated canals (n = 30 per group)

<table>
<thead>
<tr>
<th></th>
<th>New</th>
<th>Used</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>PTG</td>
<td>PTN</td>
</tr>
<tr>
<td>Mean Torque (Ncm)</td>
<td>1.85&lt;sub&gt;a&lt;/sub&gt;,1 (0.23)</td>
<td>0.81&lt;sub&gt;b&lt;/sub&gt;,1 (0.1)</td>
</tr>
<tr>
<td>Mean Angle (°)</td>
<td>238.36&lt;sub&gt;a&lt;/sub&gt;,1 (39.46)</td>
<td>165.35&lt;sub&gt;b&lt;/sub&gt;,1 (15.92)</td>
</tr>
</tbody>
</table>

Different subscript letters in the same row of the new or used grouping indicate statistical significant difference between groups (1-way ANOVA post hoc Bertoni test, P < .05). Different subscript numbers in the same row indicate statistical significant differences between new and used instruments of the same kind.
2. Figures

Figure 1. Sample of a simulated canal in a resin block. The canals were 17-mm long and 0.015 mm in diameter, with a 45° curve at 11 mm and a second 45° curve at 20 mm.
Figure 2. Set-up of the testing equipment used to perform torsional fatigue testing. (a) reversible geared motor; (b) contactless rotary sensor; (c) plastic gears with a 4:1 ratio; (d) hardened steel chuck; (e) torque-sensor and attached hardened chuck; and (f) freely moving stable track.
Figure 3. Representative torque profile of ProTaper Gold (PTG) F2 tested unused or after use to instrument two simulated canals. The torque and angle at fracture are indicated in the Y- and X-axis, respectively. The red dashed line (---) indicates new instruments and the blue line instruments used to instrument 2 resin blocks.
Figure 4. Representative torque profile of ProTaper Next (PTN) X2 tested unused or after use to instrument two simulated canals. The torque and angle at fracture are indicated in the Y- and X-axis, respectively. The red dashed line (----) indicates new instruments and the blue line instruments used to instrument 2 resin blocks.
Figure 5. Representative torque profile of ProTaper Universal (PTU) F2 tested unused or after use to instrument two simulated canals. The torque and angle at fracture are indicated in the Y- and X-axis, respectively. The red dashed line (-----) indicates new instruments and the blue line instruments used to instrument 2 resin blocks.
Figure 6. Scanning electron micrographs (200x and 1000x) of ProTaper Gold (PTG) F2 tested unused or after use to instrument two simulated canals.
Figure 7. Scanning electron micrographs (200x and 1000x) of ProTaper Next (PTN) X2 tested unused or after use to instrument two simulated canals.
Figure 8. Scanning electron micrographs (200x and 1000x) of ProTaper Universal (PTU) F2 tested unused or after use to instrument two simulated canals.