CUTTING EFFICIENCY OF ESX, ENDOSEQUENCE, AND PROFILE INSTRUMENTS USING THE TRUETOOTH REPLICA

by

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In partial fulfillment of the requirements for the Degree of Master of Science in Endodontology

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ABSTRACT

Introduction: The newly released ESX rotary system (Brasseler USA, Savannah, GA) represents an evolution of the EndoSequence system (Brasseler) with an improved design and streamlined protocol. This study compared the cutting efficiency of three rotary instrument systems: ESX, EndoSequence and ProFile (Dentsply, Tulsa, OK) using the TrueTooth Replica (Dental Education Laboratories, Santa Barbara, CA).

Methods: Forty-five maxillary molar TrueTooth Replicas (3-001) were divided into three groups (n=15) for instrumentation with ProFile 60.04-35.04, EndoSequence 60.04-35.04 or ESX 55.04-35.04. After coronal access, baseline weight (±0.00001 g) was measured on an analytical balance. Canals were instrumented to 55.04 for the palatal and 35.04 for the mesio-buccal and disto-buccal using a crown-down technique, irrigated with isopropyl alcohol, dried thoroughly, and reweighed. All files were single use. Instrumentation cutting time was recorded. Groups were compared for weight reduction, cutting time, and cutting efficiency (weight reduction/second) using one-way ANOVA and Tukey's tests ($\alpha = 0.05$).

Results: EndoSequence demonstrated significantly greater weight reduction (0.0205 g ± 0.0033 g) compared to ProFile (0.0176 g ± 0.0019 g) ($p<0.05$) and ESX (0.0170 g ± 0.0032 g) ($p<0.01$) with no difference between ESX and ProFile. Cutting time was significantly shorter with ESX (29.23 sec ± 3.84 sec) compared to ProFile (83.30 sec ± 11.82 sec) ($p<0.0001$) and EndoSequence (49.17 sec ± 2.49 sec) ($p<0.0001$). Cutting efficiency was significantly greater for ESX (0.0006 g/sec ± 0.00014 g/sec) compared to ProFile (0.0002 g/sec ± 0.00004 g/sec) (p<0.0001) and EndoSequence (0.0004 g/sec ± 0.00006 g/sec) (p<0.05), and for EndoSequence compared to ProFile (p<0.05).

Conclusion: Cutting efficiency differed between the three rotary systems, being significantly greater for ESX as compared to both ProFile and EndoSequence. All rotary instruments used in the study conformed to ISO standards with regard to cross-sectional diameter and taper. The TrueTooth replica proved to be a standardized model in which to test endodontic instrumentation.

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CHAPTER 1. INTRODUCTION AND REVIEW OF THE LITERATURE

Mechanical instrumentation of the canal system is one of the key steps in endodontic therapy. Bystrom and Sundqvist (1) and Dalton *et al.* (2) have demonstrated that mechanical instrumentation with files, using a saline irrigant only, could reduce the bacterial load in root canals of previously infected teeth. Schilder (3) and Buchanan (4) have recognized and advocated for the importance of instrumentation as a means to not only allow for effective antimicrobial irrigation but also to provide space for a good quality obturation. Successful endodontic therapy is predicated on mechanical instrumentation that not only reduces microbiological contamination but also plays a role in the prevention of reinfection.

Nickel titanium instruments. Efficiency in endodontic instrumentation relies on files that require fewer rotations and less time to enlarge a canal, while undergoing less fatigue to accomplish this task (5). Studies have demonstrated that nickel-titanium instruments are oftentimes as effective, if not more effective, than instruments made out of stainless steel in removing dentin despite their superelasticity and tendency to deflect from dentin when apical pressure is applied (6). Nickel-titanium instruments have been proven to be faster than hand instrumentation and to produce less fatigue (7-9). The development of novel designs for nickel-titanium files is an attempt to further maximize the efficiency of rotary instrumentation, allowing clinicians to predictably and proficiently create ideally tapered endodontic preparations (3) while minimizing procedural misadventures (10).

Cutting efficiency parameters. The cutting efficiency of an endodontic file is dependent on a number of parameters, including but not limited to metallurgical properties, cross-sectional geometry, tip design, rake angle, radial landing, helical angulation, and pitch (11-16). The application of particular surface treatments to nickel-titanium files, such as thermal nitridation and nitrogen-ionic implantation, has been purported to produce higher wear resistance and an increased cutting capacity (17). Electro-polishing, an alternative surface treatment whereby superficial imperfections are removed, has similarly been claimed to produce sharper instruments with increased cutting efficiency (18). Endodontic nickel-titanium rotary systems vary in terms of these characteristics, reflecting differences in thought regarding efficient canal preparation.

Instrument size. The size, or rather the cross-sectional diameter of a rotary file has as well been demonstrated to play a role in its cutting efficiency. In an evaluation of root canal instruments used in a rotary motion, Villalobos *et al.* (19) found that size 70 files required less time than size 50 files to enlarge predrilled simulated canals in bovine bone. Perhaps even with the comparison of two similar files, it could be extrapolated that the larger of the two may be more stiff and occupy more space, thus being better equipped to remove dentin. Thus, the International Organization for Standardization (ISO) as well as the American Dental Association have established specifications and tolerance limits concerning such physical characteristics of files as diameter and taper. In accordance with ISO standard 3630-1, file diameter can vary up to 0.03 mm (ISO 3630-1, Second Edition 2008-02-01). The manufacturing of endodontic files is intended to conform to these aforementioned guidelines to ensure consistency in instrumentation.

ProFile. ProFile rotary files (Dentsply, Tulsa Dental Specialties, Tulsa, OK) have maintained an established position as a multi-file system in endodontic instrumentation for over two decades. The files are manufactured with conventional nickel-titanium alloy and are characterized by a constant taper design, 20^o helical angle, and constant pitch. Each file is composed of a special safety-tip with a minimal transition angle, to prevent ledging and transportation of the canal, and radial-landed U file flutes, which are purported to efficiently move debris coronally as the neutral rake angle planes dentinal walls. The design features of this file system are intended to allow for a crown down, continuously tapering preparation from orifice to apex.

EndoSequence. EndoSequence rotary files (Brasseler USA, Savannah, GA; Real World Endo, Wilmington, DE) are as well made from conventional nickel-titanium alloy and intended to be utilized in a sequenced crown down fashion, but are instead ground from a triangular blank with alternating contact points along the cutting length of the instrument. This design is intended to keep the file centered in the canal while limiting dentinal wall contact. Although the file is never fully engaged along its entire length, the alternate contact points promote efficient three dimensional cleaning as the sharp cutting edges engage canal walls at opposing intervals. The lack of radial lands decreases the thickness of metal creating a more flexible file which can operate at a lower torque and higher speed thereby reducing stress on the file and the root canal wall. Other salient features of the file include a noncutting tip, an electropolished surface, and variable pitch and helical angles aimed to reduce the tendency to screw into the canal. Prior to the use of the EndoSequence system proper, a preliminary Expeditor file (27.04) is intended to be used in order to gauge the canal system to be shaped. As its name implies, the Expeditor file expedites instrumentation by providing information to the clinician in the form of resistance on appropriate final canal size.

ESX. Recently, Brasseler introduced the ESX rotary file system (Brasseler USA), representing an evolution of the EndoSequence system. There are numerous similarities to the EndoSequence system, including fabrication with conventional nickel-titanium alloy, triangular cross-sectional file geometry, alternate contact points, surface electropolishing, and a preliminary Expeditor file (15.05) also intended to estimate canal size despite its difference in tip and taper. The ESX rotary file system, however, is characterized by a performance enhancing ‘booster tip’ comprised of six cutting edges within the first millimeter of the instrument. The novel tip design boasts an anti-ledging and anti-perforating centering mechanism and is claimed to allow for fewer instruments and larger diameter increases. As such, following the creation of a glide path by the Expeditor, a single ESX file is intended to complete canal shaping. The ESX rotary system is thus, in its basic form, a two file system.

The characteristics of the three endodontic file systems ProFile, EndoSequence, and ESX are further compared and contrasted in Table 1.

Table 1. Comparison between ProFile, EndoSequence, and ESX

	ProFile	EndoSequence	ESX
Metallurgy	Conventional nitinol	Conventional nitinol	Conventional nitinol
Taper	Constant .04	Constant .04	Constant .04
Cross Sectional Geometry	U-shaped	Triangular with alternating cutting edges	Triangular with alternating cutting edges
Rake Angle	Neutral	Negative	Negative
Cutting Blades	Passive	Active	Active
Radial-Landing	Flat	Non-landed	Non-landed
Tip Design	Non-cutting	Non-cutting 'precision tip' (active at D1)	Non-cutting 'booster tip' (6 small cutting sides)
Pitch	Constant	Variable	Variable
Helical Angle	20°	Variable	Variable
Surface Treatment	Not Treated	Electropolished	Electropolished
Recommended Speed (rpm)	150-300	500	500

Assessment of cutting efficiency. The comparison of cutting efficiency amongst different nickel-titanium rotary files presents a challenge as there are no clear standards for cutting effectiveness or sharpness of endodontic instruments (20, 21). Many approaches have been employed in the general study of cutting efficiency, examples being: assessing changes in dentin thickness and root canal volume (22); calculating weight loss of tooth samples (11), bone (23) and resin blocks (17) after instrumentation; measuring debris generated during the preparation of extracted teeth (24); measuring the mass lost from a Plexiglas plate (25); the maximum penetration depth of an instrument into a Plexiglas plate (26), or simulated cylindrical canal (14); and in terms of preparation time in extracted teeth (27) or bovine bone (19). Even recently yet another approach to the evaluation of cutting efficiency has been discussed, employing a methodology based on measurements of torque and apical force in nickel-titanium instruments during controlled use in simulated canals (28). Nonetheless, microcomputed tomography has at least been established as an effective adjunct in the evaluation of cutting efficiency, allowing for an increased sensitivity in the recording of such changes as canal geometry following instrumentation (29) or groove formation in bone (30). From a review of the literature, it is apparent that a ‘best procedure’ for the evaluation of cutting efficiency has not yet been established. Perhaps difficulty in coming to a consensus for the evaluation of cutting efficiency arises as many of these techniques fail to be clinically relevant, and those that attempt to be clinically relevant tend to lack standardization.

TrueTooth replica. The TrueTooth replica (Dental Education Laboratories, Santa Barbara, CA) is fabricated with great anatomical accuracy to human teeth – emulating natural pulpal anatomy in terms of canal curvatures, fins, apices, and orifices. A consistent and precise three-dimensional printing process is utilized in the fabrication of TrueTooth replicas, demanding the reproduction of clinically relevant instrument kinematics with predictability and consistency. The replica teeth are fabricated out of a transparent heat resistant engineered resin, and although softer than real dentin, provide adequate resistance to rotary instrumentation. Consequently, canals may be shaped using normal speed and torque settings for the desired rotary file. To the author's knowledge, the TrueTooth replica has not previously been employed as a model in the study of rotary instrumentation.

AIMS OF THE STUDY

1. The first aim of this present study was to evaluate the cutting efficiency of the ESX rotary instrument system as it compared to ProFile and Endosequence, while utilizing the TrueTooth replica. For purposes of this study, cutting efficiency was defined as weight change per unit time. The working hypothesis tested was that the ESX system would demonstrate superior cutting efficiency because of its improved design and streamlined protocol.

2. The second aim of the study was to evaluate how closely the ProFile, EndoSequence, and ESX files conformed to ISO guidelines for cross-sectional diameter and taper. Instrument levels D3 and D13 were measured.

3. The third aim of the study was to evaluate the level of standardization and clinical applicability of the TrueTooth replica as a novel model for the testing of endodontic instrumentation. Standardization was quantified by the pre-access weight of the replicas, whereas clinical applicability was determined through a qualitative operator assessment.

CHAPTER 2. MATERIALS AND METHODS

2.1 Pre-operative evaluation of files. Each rotary instrument was individually imaged with a stereomicroscope (SMZ-10, Nikon, Tokyo, Japan) at 170x magnification. Measurements of cross-sectional diameter and taper were made on images obtained using Dinocapture 2.0 camera/software (Dino-Lite Europe, Naarden, The Netherlands) at levels D3 and D13. 10% of the instruments were randomly selected and re-measured after two weeks to test for evaluator reproducibility. In addition, representative images of file tips of ProFile, EndoSequence and ESX rotary instruments were obtained at 369x magnification and 40° angulation using a scanning electron microscope (Quanta 200; -FEI, Hillsboro, Oregon).

2.2 Selection of TrueTooth replica. The TrueTooth maxillary molar replica 3-001 was selected based on its level of difficulty and canal curvature. The pulp chamber has moderate calcification. The mesio-buccal 1 and 2 canals each demonstrate an apical diameter of 0.22 mm with the mesio-buccal 2 canal having an apical terminus separate from that of the mesio-buccal 1. The two mesio-buccal canals communicate through mid-root isthmuses and bifurcate in the last 1-2 mm. The disto-buccal canal has a slight S-curve and trifurcates in the final 3 mm demonstrating an apical diameter of 0.14 mm. The palatal canal has a large apical diameter of 0.39 mm and depicts a sharp buccal turn as it exits the root. (Table 2)

2.3 Instrumentation of TrueTooth replicas. One operator (AP) proficient in the rotary file techniques performed all procedures. The palatal, disto-buccal and mesio-buccal-1 canals of each TrueTooth maxillary molar replica (3-001) were instrumented. Instrumentation of the mesio-buccal 2 canal was not included in this study due to its level of curvature and constriction, which necessitated more elaborate hand instrumentation and coronal flaring. On completion of coronal access cavity preparation, the three main canals were negotiated up to a size 15 K-type file (FlexoFile, Dentsply Maillefer, Ballaigues, Switzerland) to the major apical foramen as observed at 4x magnification. The working length was established at 0.5 mm short of the portal of exit. Rotary instruments were used according to the manufacturers' recommendations (300 rpm for ProFile, 500 rpm for EndoSequence and ESX). Each rotary file was utilized in a single TrueTooth Replica.

TrueTooth replicas were irrigated with 70% isopropyl alcohol (Techspray, Kennesaw, GA) as per manufacturer's recommendations. Irrigation (0.25 mL per canal) was used between instruments. Irrigant was delivered using a 27 gauge side-vented Max-i-Probe needle (Dentsply) placed into the canal as deep as would passively fit but not beyond working length.

A crown down preparation was accomplished by taking the ProFile and EndoSequence rotary instruments to engagement and back three times with light apical pressure. The single stroke and clean technique as recommended by Brasseler was employed for the ESX rotary instruments. Canal size and thus final instrumentation size were determined during the pilot study with the aid of the Expeditor files from both EndoSequence and ESX. Patency was established and maintained throughout instrumentation with a size 10 K-type file for all groups.

For ProFile (n=15) and EndoSequence (n=15) groups, instrumentation was completed with the 60.04 and 55.04 rotary instruments for the palatal canal, and 50.04, 45.04, 40.04, and 35.04 for the mesio-buccal 1 and disto-buccal canals. For the ESX group (n=15), the ESX expeditor file 15.05 was first taken to working length; instrumentation of the palatal canal was completed with the 55.04 rotary instrument and the mesio-buccal 1 and disto-buccal canals with the 35.04.

2.4 Measurement of weight reduction, instrumentation cutting time and cutting efficiency. For purposes of this study, weight reduction of the TrueTooth replicas exemplified the removal of intracanal dentin which occurs clinically during cleaning and shaping with rotary instrumentation. On completion of the coronal access cavity, the baseline weight (±0.00001 g) of each TrueTooth replica was measured on an analytical balance (Mettler Instrument Corp., Hightstown, NJ). After each instrument, root canals were dried by the placement of a single paper point in each canal and application of pressurized air, and the tooth replica was reweighed. Forty-five intact TrueTooth replicas not utilized in the study proper were weighed in order to evaluate consistency in pre-access weight. Instrument cutting time (seconds) was measured utilizing a digital chronometer. Only actual cutting time was calculated - the time required for the changing of instruments or irrigation was not considered. Gloves were worn at all times during the handling of the tooth replicas in order to prevent contamination with skin oils.

2.5 Statistical analysis. A power analysis (www.statstodo.com) conducted from a pilot study of five TrueTooth replicas per rotary system (Appendix 1) determined a sample size of 15 (80% power) (Appendix 2). Pearson’s correlation coefficient was used to evaluate the reproducibility of file diameter measurements taken two weeks apart.

Normal distribution of experimental data was confirmed by using Kolmogorov-Smirnov tests. Intergroup comparisons for weight reduction, instrument cutting time, and cutting efficiency (weight reduction/second) were made with one-way ANOVA and Tukey’s tests (Prism 6 for Macintosh software, GraphPad Software, Inc. La Jolla, CA). Intragroup comparisons were made with repeated measures one-way ANOVA and Tukey’s tests. The level of significance was set at $\alpha = 0.05$.

Table 2. Characteristics of the TrueTooth replica 3-001

	MB1	MB2	DB	P
Coronal Canal Curvature	Severe	Severe	N/A	N/A
Coronal Canal Size	Medium	Medium	Medium	Medium
Coronal Impediments	N/A	Yes	N/A	N/A
Apical Canal Curvatures	Slight	Slight	N/A	N/A
Apical Canal Size	Small	Small	Small	Medium
Apical Impediments	Yes	Yes	Yes	Yes

CHAPTER 3. RESULTS

3.1 Evaluation of rotary instruments. All rotary instruments used in the study conformed to ISO standards with regard to cross-sectional diameter and taper (Table 3). Intraobserver reproducibility of file diameter measurements was high (*r* = 0.9996). No instrument separated during instrumentation. SEM images showed differences in external smoothness and tip geometry of the ProFile, EndoSequence, and ESX rotary instruments (Figure 1).

3.2 Pre-access evaluation of TrueTooth replicas. The weights of the intact 45 TrueTooth replica were found to range from 1.9054 g to 1.9883 g (mean 1.9289 g ± 0.0250 g) (Table 4).

3.3 Intergroup assessments. Data for weight change, cutting time, and cutting efficiency are presented in Tables 5, 6, and 7 respectively. There were no significant differences between groups in TrueTooth baseline weight (ProFile: 1.7920 g ± 0.0130 g; EndoSequence: 1.7944 g ± 0.0140 g; ESX 1.8030 g ± 0.0116 g) (Figure 2A). Weight reduction at the completion of instrumentation was significantly greater for EndoSequence (0.0205 g ± 0.0033 g) compared to ProFile (0.0176 g ± 0.0019 g) ($p<0.05$) and ESX (0.0170 g ± 0.0032 g) ($p<0.01$), with no difference between ProFile and ESX (Figure 2B). ESX required significantly less cutting time (29.23 sec ± 3.84 sec) compared to ProFile (83.30 sec ± 11.82 sec) ($p<0.0001$) and EndoSequence (49.17 sec ± 2.49 sec) ($p<0.0001$), whereas EndoSequence required significantly less cutting time (49.17 sec ± 2.49 sec) ($p<0.0001$) than ProFile (83.30 sec ± 11.82 sec) ($p<0.0001$) (Figure 2C). Cutting efficiency was significantly greater for ESX (0.0006 g/sec ± 0.00014 g/sec) compared to

ProFile (0.0002 g/sec ± 0.00004 g/sec) ($p<0.0001$) and EndoSequence (0.0004 g/sec ± 0.00006 g/sec) ($p<0.05$), with the efficiency of EndoSequence being significantly greater than that of ProFile ($p<0.05$) (Figure 2D).

3.4 Intragroup assessments. As expected, significantly greater weight reduction occurred with the use of larger files (60.04 for ProFile and EndoSequence, 55.04 for the ESX); however, within each system there was no significant difference between the smaller files in generating weight reduction (Figure 3 B-D). There were significant intragroup differences in cutting time for each rotary system ($p<0.0001$), with longer times required for files used in two canals (MB1 and DB; 50.04, 45.04, 40.04, 35.04) compared to a single canal (P; 60.04 and 55.04) (Figure 3A).

3.5 Post-hoc power analysis. A post-hoc power analysis (www.statstodo.com) was conducted utilizing data obtained from the cutting efficiency calculations. The power of this study was found to be 99% (Appendix 3).

Table 3(a). File diameter evaluations with ISO 3630-1 tolerance of ± 0.03, ProFile

Files	Expected diameter (mm)			ProFile														
Exp15.05 d3	0.30	0.27	0.33															
60.04 d3	0.72	0.69	0.75	0.74	0.75	0.72	0.73	0.72	0.71	0.72	0.74	0.73	0.72	0.72	0.74	0.72	0.73	0.71
55.04 d3	0.67	0.64	0.70	0.67	0.67	0.69	0.69	0.67	0.68	0.67	0.68	0.67	0.68	0.68	0.68	0.67	0.66	0.69
50.04 d3	0.62	0.59	0.65	0.63	0.64	0.63	0.63	0.62	0.63	0.63	0.63	0.64	0.64	0.63	0.63	0.61	0.64	0.64
45.04 d3	0.57	0.54	0.60	0.57	0.58	0.59	0.57	0.59	0.58	0.57	0.58	0.57	0.57	0.58	0.58	0.58	0.58	0.60
40.04 d3	0.52	0.49	0.55	0.54	0.53	0.54	0.52	0.53	0.53	0.53	0.53	0.54	0.53	0.54	0.53	0.51	0.54	0.54
35.04 d3	0.47	0.44	0.50	0.49	0.48	0.49	0.48	0.50	0.50	0.48	0.48	0.48	0.48	0.49	0.48	0.47	0.49	0.47
Exp15.05 d13	0.80	0.77	0.83															
60.04 d13	1.12	1.09	1.15	1.11	1.12	1.14	1.12	1.11	1.13	1.12	1.15	1.13	1.10	1.11	1.10	1.12	1.11	1.10
55.04 d13	1.07	1.04	1.10	1.05	1.06	1.09	1.07	1.07	1.07	1.07	1.08	1.07	1.07	1.06	1.07	1.06	1.05	1.09
50.04 d13	1.02	0.99	1.05	1.02	1.04	1.02	1.03	1.01	1.04	1.03	1.04	1.03	1.03	1.02	1.01	1.03	1.03	1.03
45.04 d13	0.97	0.94	1.00	0.99	0.99	0.98	0.97	0.98	0.96	0.98	0.98	1.00	0.96	0.98	0.97	0.97	0.97	0.97
40.04 d13	0.92	0.89	0.95	0.93	0.91	0.92	0.93	0.93	0.91	0.92	0.91	0.91	0.92	0.91	0.91	0.92	0.92	0.90
35.04 d13	0.87	0.84	0.90	0.89	0.87	0.86	0.88	0.89	0.88	0.87	0.88	0.85	0.87	0.87	0.86	0.86	0.86	0.85

Table 3(b). File diameter evaluations with ISO 3630-1 tolerance of ± 0.03, EndoSequence

Files	Expected diameter (mm)			EndoSequence														
Exp15.05 d3	0.30	0.27	0.33															
60.04 d3	0.72	0.69	0.75	0.71	0.72	0.73	0.73	0.71	0.72	0.72	0.73	0.72	0.70	0.74	0.71	0.73	0.74	0.71
55.04 d3	0.67	0.64	0.70	0.67	0.69	0.68	0.69	0.66	0.68	0.70	0.69	0.67	0.67	0.68	0.66	0.69	0.68	0.67
50.04 d3	0.62	0.59	0.65	0.63	0.64	0.62	0.62	0.63	0.62	0.64	0.62	0.64	0.62	0.64	0.63	0.61	0.64	0.62
45.04 d3	0.57	0.54	0.60	0.56	0.58	0.58	0.56	0.57	0.57	0.58	0.58	0.59	0.59	0.59	0.59	0.58	0.58	0.58
40.04 d3	0.52	0.49	0.55	0.53	0.53	0.53	0.52	0.53	0.52	0.52	0.53	0.52	0.51	0.54	0.54	0.52	0.53	0.54
35.04 d3	0.47	0.44	0.50	0.48	0.49	0.47	0.47	0.49	0.50	0.48	0.49	0.48	0.49	0.49	0.47	0.48	0.48	0.46
Exp15.05 d13	0.80	0.77	0.83															
60.04 d13	1.12	1.09	1.15	1.07	1.10	1.12	1.10	1.12	1.09	1.12	1.10	1.10	1.13	1.10	1.11	1.10	1.11	1.10
55.04 d13	1.07	1.04	1.10	1.05	1.07	1.06	1.05	1.08	1.05	1.06	1.08	1.05	1.06	1.06	1.07	1.07	1.05	1.08
50.04 d13	1.02	0.99	1.05	0.99	1.01	1.01	1.00	1.01	1.02	1.01	1.01	1.00	1.01	0.99	1.01	1.00	1.02	1.00
45.04 d13	0.97	0.94	1.00	0.94	0.95	0.87	0.94	0.97	0.95	0.94	0.97	0.96	0.96	0.97	0.95	0.95	0.96	0.95
40.04 d13	0.92	0.89	0.95	0.90	0.89	0.90	0.93	0.90	0.92	0.90	0.90	0.90	0.91	0.93	0.92	0.89	0.90	0.89
35.04 d13	0.87	0.84	0.90	0.86	0.86	0.85	0.86	0.87	0.87	0.85	0.87	0.87	0.85	0.87	0.87	0.86	0.86	0.86

Table 3(c). File diameter evaluations with ISO 3630-1 tolerance of ± 0.03, ESX

Files	Expected diameter (mm)			ESX														
Exp15.05 d3	0.30	0.27	0.33	0.32	0.31	0.31	0.31	0.31	0.32	0.31	0.33	0.29	0.31	0.32	0.31	0.31	0.32	0.30
60.04 d3	0.72	0.69	0.75															
55.04 d3	0.67	0.64	0.70	0.69	0.69	0.69	0.68	0.69	0.67	0.67	0.67	0.67	0.67	0.67	0.68	0.67	0.67	0.68
50.04 d3	0.62	0.59	0.65															
45.04 d3	0.57	0.54	0.60															
40.04 d3	0.52	0.49	0.55															
35.04 d3	0.47	0.44	0.50	0.48	0.46	0.46	0.47	0.48	0.48	0.48	0.48	0.47	0.47	0.48	0.46	0.48	0.49	0.46
Exp15.05 d13	0.80	0.77	0.83	0.78	0.79	0.78	0.78	0.78	0.79	0.80	0.80	0.80	0.78	0.79	0.79	0.77	0.79	0.79
60.04 d13	1.12	1.09	1.15															
55.04 d13	1.07	1.04	1.10	1.05	1.05	1.06	1.05	1.06	1.05	1.06	1.07	1.06	1.07	1.06	1.08	1.06	1.07	1.07
50.04 d13	1.02	0.99	1.05															
45.04 d13	0.97	0.94	1.00															
40.04 d13	0.92	0.89	0.95															
35.04 d13	0.87	0.84	0.90	0.88	0.85	0.87	0.86	0.86	0.89	0.88	0.89	0.88	0.87	0.89	0.87	0.89	0.87	0.89

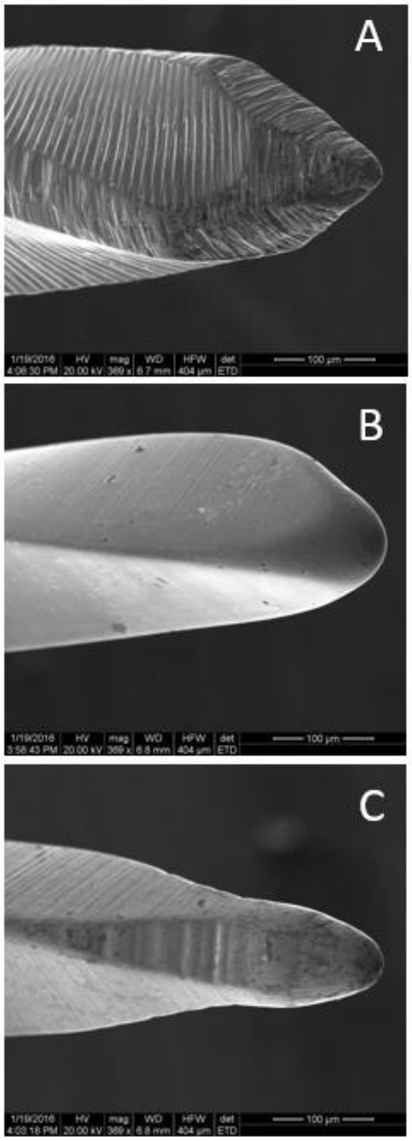

Figure 1. SEM images of rotary file tips (A) Profile, (B) EndoSequence, and (C) ESX with Booster Tip. Images captured at 369 X magnification and 40° angulation (Quanta 200 FEI, Japan).

Table 4. Pre-access TrueTooth replica weight

Tooth #	Weight (g)
1	1.9650
2	1.9116
3	1.9230
4	1.9085
5	1.9621
6	1.9510
7	1.9196
8	1.9775
9	1.9113
10	1.9140
11	1.9070
12	1.9092
13	1.9163
14	1.9466
15	1.9773
16	1.9060
17	1.9162
18	1.9174
19	1.9207
20	1.9181
21	1.9720
22	1.9163
23	1.9124
24	1.9726
25	1.9534
26	1.9054
27	1.9177
28	1.9062
29	1.9170
30	1.9412
31	1.9493
32	1.9883
33	1.9159
34	1.9095
35	1.9194
36	1.9153
37	1.9100
38	1.9161
39	1.9067
40	1.9197
41	1.9148
42	1.9598
43	1.9085
44	1.9263
45	1.9144
Max	1.9883
Min	1.9054
Mean	1.9289
SD	0.0250

Table 5(a). ProFile weight change

				Reduction by file (g)					
Tooth #	Baseline weight (g)	Final weight (g)	Total weight reduction (g)	**60.04**	**55.04**	**50.04**	**45.04**	**40.04**	**35.04**
1	1.7942	1.7758	0.0184	0.0028	0.0049	0.0015	0.0044	0.0030	0.0018
2	1.7788	1.7640	0.0148	0.0032	0.0030	0.0036	0.0020	0.0013	0.0017
3	1.8062	1.7910	0.0152	0.0047	0.0009	0.0051	0.0024	0.0008	0.0013
4	1.7773	1.7572	0.0201	0.0045	0.0009	0.0085	0.0010	0.0033	0.0019
5	1.7902	1.7726	0.0176	0.0032	0.0055	0.0014	0.0015	0.0026	0.0034
6	1.7978	1.7821	0.0157	0.0058	0.0043	0.0022	0.0007	0.0020	0.0007
7	1.7833	1.7682	0.0151	0.0056	0.0011	0.0031	0.0016	0.0026	0.0011
8	1.8042	1.7851	0.0191	0.0052	0.0053	0.0016	0.0041	0.0003	0.0026
9	1.7929	1.7725	0.0204	0.0093	0.0002	0.0026	0.0010	0.0019	0.0054
10	1.7871	1.7684	0.0187	0.0076	0.0019	0.0020	0.0023	0.0011	0.0038
11	1.7944	1.7755	0.0189	0.0086	0.0011	0.0020	0.0009	0.0036	0.0027
12	1.7664	1.7482	0.0182	0.0097	0.0002	0.0018	0.0023	0.0037	0.0005
13	1.7895	1.7736	0.0159	0.0079	0.0007	0.0033	0.0004	0.0021	0.0015
14	1.8200	1.8032	0.0168	0.0085	0.0001	0.0024	0.0010	0.0004	0.0044
15	1.7971	1.7785	0.0186	0.0077	0.0010	0.0022	0.0016	0.0027	0.0034
Mean	**1.7920**	**1.7744**	**0.0176**	**0.0063**	**0.0021**	**0.0029**	**0.0018**	**0.0021**	**0.0024**
SD	0.0130	0.0133	0.0019	0.00233	0.002	0.0018	0.0012	0.0011	0.0014

Table 5(b). EndoSequence weight change

				Reduction by file (g)					
Tooth #	Baseline weight (g)	Final weight (g)	Total weight reduction (g)	**60.04**	**55.04**	**50.04**	**45.04**	**40.04**	**35.04**
1	1.8172	1.7911	0.0261	0.0076	0.0026	0.0035	0.0036	0.0049	0.0039
2	1.7945	1.7700	0.0245	0.0095	0.0014	0.0071	0.0002	0.0036	0.0027
3	1.8132	1.7951	0.0181	0.0057	0.0059	0.0010	0.0048	0.0005	0.0002
4	1.7770	1.7600	0.0170	0.0084	0.0015	0.0009	0.0008	0.0032	0.0022
5	1.8204	1.8038	0.0166	0.0066	0.0028	0.0004	0.0010	0.0030	0.0028
6	1.7946	1.7703	0.0243	0.0090	0.0018	0.0031	0.0024	0.0048	0.0032
7	1.7815	1.7641	0.0174	0.0029	0.0055	0.0019	0.0036	0.0001	0.0034
8	1.7772	1.7591	0.0181	0.0090	0.0002	0.0030	0.0025	0.0005	0.0029
9	1.7993	1.7822	0.0171	0.0077	0.0013	0.0018	0.0027	0.0002	0.0034
10	1.7795	1.7625	0.0170	0.0081	0.0004	0.0017	0.0039	0.0004	0.0025
11	1.7872	1.7649	0.0223	0.0089	0.0018	0.0036	0.0028	0.0033	0.0019
12	1.7855	1.7635	0.0220	0.0085	0.0012	0.0018	0.0037	0.0041	0.0027
13	1.7935	1.7720	0.0215	0.0065	0.0016	0.0025	0.0041	0.0021	0.0047
14	1.7943	1.7726	0.0217	0.0088	0.0017	0.0049	0.0021	0.0014	0.0028
15	1.8016	1.7781	0.0235	0.0096	0.0012	0.0038	0.0032	0.0017	0.0040
Mean	**1.7944**	**1.7740**	**0.0205**	**0.00779**	**0.0021**	**0.0027**	**0.0028**	**0.0023**	**0.0029**
SD	0.0140	0.0136	0.0033	0.0018	0.0016	0.0017	0.0013	0.0017	0.0010

Table 5(c). ESX weight change

				Reduction by file (g)		
Tooth #	Baseline weight (g)	Final weight (g)	Total weight reduction (g)	**Exp15.05**	**55.04**	**35.04**
1	1.7954	1.7773	0.0181	0.0043	0.0075	0.0063
2	1.8189	1.8007	0.0182	0.0095	0.0046	0.0041
3	1.8062	1.7916	0.0146	0.0034	0.0073	0.0039
4	1.8096	1.7888	0.0208	0.0078	0.0073	0.0057
5	1.8106	1.7940	0.0166	0.0039	0.0089	0.0038
6	1.8087	1.7962	0.0125	0.0019	0.0073	0.0033
7	1.8167	1.8035	0.0132	0.0051	0.0073	0.0008
8	1.7786	1.7583	0.0203	0.0045	0.0079	0.0079
9	1.7944	1.7822	0.0122	0.0032	0.0047	0.0043
10	1.8059	1.7921	0.0138	0.0059	0.0089	0.0010
11	1.8068	1.7880	0.0188	0.0087	0.0048	0.0053
12	1.8002	1.7785	0.0217	0.0074	0.0075	0.0068
13	1.7826	1.7641	0.0185	0.0052	0.0081	0.0052
14	1.8123	1.7921	0.0202	0.0045	0.0091	0.0066
15	1.7960	1.7803	0.0157	0.0030	0.0076	0.0051
Mean	**1.8029**	**1.7858**	**0.0170**	**0.0052**	**0.0073**	**0.0047**
SD	0.0116	0.0126	0.0032	0.0022	0.0015	0.002

Table 6(a). ProFile cutting time

Tooth #	Total time (sec)	Time by file (sec)					
		60.04	55.04	50.04	45.04	40.04	35.04
1	96.15	8.05	6.04	21.00	23.00	19.68	18.38
2	97.00	8.08	8.00	24.11	23.08	16.71	17.02
3	96.67	8.45	7.92	22.62	23.54	18.57	15.57
4	95.89	6.30	7.78	22.37	23.09	19.03	17.32
5	95.00	6.09	6.35	24.07	22.31	21.14	15.04
6	94.17	6.35	6.95	21.34	23.20	18.79	17.54
7	86.91	7.27	6.35	19.83	17.53	17.86	18.07
8	83.62	8.26	7.27	15.24	20.58	15.70	16.57
9	77.88	7.14	7.33	12.44	16.31	17.19	17.47
10	73.79	6.74	7.13	16.09	17.92	14.20	11.71
11	72.51	6.09	6.87	13.61	14.60	16.49	14.85
12	67.33	6.68	6.62	12.50	14.33	12.62	14.58
13	66.44	6.03	7.28	12.30	14.59	14.34	11.90
14	70.50	5.97	6.47	13.35	14.60	15.57	14.54
15	75.60	5.96	7.13	14.50	15.57	15.70	16.74
Mean	**83.30**	**6.90**	**7.03**	**17.69**	**18.95**	**16.91**	**15.82**
SD	11.82	0.91	0.59	4.59	3.81	2.31	2.060

Table 6(b). EndoSequence cutting time

Tooth #	Total time (sec)	Time by file (sec)					
		60.04	55.04	50.04	45.04	40.04	35.04
1	55.25	4.79	3.47	10.34	12.88	13.67	10.10
2	51.46	4.92	4.01	9.62	13.47	10.53	8.91
3	47.83	4.90	6.42	9.89	8.38	9.22	9.02
4	49.72	4.27	5.11	8.58	10.43	12.89	8.44
5	49.93	4.61	4.73	10.15	11.52	10.07	8.85
6	49.28	4.01	5.51	9.88	11.46	11.08	7.34
7	51.28	3.99	3.73	10.90	11.06	10.28	11.32
8	47.96	3.96	4.41	10.23	11.51	10.70	7.15
9	49.44	3.74	4.46	8.96	11.99	11.14	9.15
10	46.26	4.14	4.92	8.51	8.96	9.04	10.69
11	49.40	4.12	5.70	9.70	10.40	10.50	8.98
12	48.74	4.20	5.85	9.56	9.37	11.51	8.25
13	44.09	3.80	4.14	8.26	8.98	9.49	9.42
14	48.89	3.99	6.15	8.96	9.23	9.74	10.82
15	48.00	3.67	4.53	9.37	10.15	9.29	10.99
Mean	**49.17**	**4.21**	**4.88**	**9.53**	**10.65**	**10.61**	**9.30**
SD	2.49	0.41	0.89	0.75	1.51	1.32	1.27

Table 6(c). ESX cutting time

Tooth #	Total time (sec)	Time by file (sec) exp15.05	55.04	35.04
1	37.31	17.81	7.06	12.44
2	34.65	16.63	6.62	11.40
3	32.36	19.56	2.82	9.98
4	24.68	12.11	2.68	9.89
5	29.84	18.55	4.20	7.09
6	24.90	10.42	2.56	11.92
7	28.44	11.66	3.80	12.98
8	27.89	11.51	3.88	12.50
9	26.34	10.21	4.60	11.53
10	33.37	16.68	4.00	12.69
11	29.73	12.63	3.09	14.01
12	24.78	9.69	3.69	11.40
13	28.36	12.70	3.21	12.45
14	30.13	13.23	3.67	13.23
15	25.68	11.26	3.09	11.33
Mean	**29.23**	**13.64**	**3.93**	**11.66**
SD	3.84	3.28	1.32	1.69

Table 7. ProFile, EndoSequence, and ESX cutting efficiency

Efficiency [weight reduction (g)/sec]

	ProFile			**EndoSequence**			**ESX**		
Tooth	**Weight**	**Time**	**Weight/Sec**	**Weight**	**Time**	**Weight/Sec**	**Weight**	**Time**	**Weight/Sec**
1	0.0184	96.15	0.0002	0.0261	55.25	0.0005	0.0181	37.31	0.0005
2	0.0148	97.00	0.0002	0.0245	51.46	0.0005	0.0182	34.65	0.0005
3	0.0152	96.67	0.0002	0.0181	47.83	0.0004	0.0146	32.36	0.0005
4	0.0201	95.89	0.0002	0.0170	49.72	0.0003	0.0208	24.68	0.0008
5	0.0176	95.00	0.0002	0.0166	49.93	0.0003	0.0166	29.84	0.0006
6	0.0157	94.17	0.0002	0.0243	49.28	0.0005	0.0125	24.90	0.0005
7	0.0151	86.91	0.0002	0.0174	51.28	0.0003	0.0132	28.44	0.0005
8	0.0191	83.62	0.0002	0.0181	47.96	0.0004	0.0203	27.89	0.0007
9	0.0204	77.88	0.0003	0.0171	49.44	0.0003	0.0122	26.34	0.0005
10	0.0187	73.79	0.0003	0.0170	46.26	0.0004	0.0138	33.37	0.0004
11	0.0189	72.51	0.0003	0.0223	49.40	0.0005	0.0188	29.73	0.0006
12	0.0182	67.33	0.0003	0.0220	48.74	0.0005	0.0217	24.78	0.0009
13	0.0159	66.44	0.0002	0.0215	44.09	0.0005	0.0185	28.36	0.0007
14	0.0168	70.50	0.0002	0.0217	48.89	0.0004	0.0202	30.13	0.0007
15	0.0186	75.60	0.0002	0.0235	48.00	0.0005	0.0157	25.68	0.0006
Mean	**0.0176**	**83.30**	**0.0002**	**0.0205**	**49.17**	**0.0004**	**0.0170**	**29.23**	**0.0006**
SD	**0.0019**	**11.82**	**0.0000**	**0.0033**	**2.49**	**0.0001**	**0.0032**	**3.84**	**0.0001**

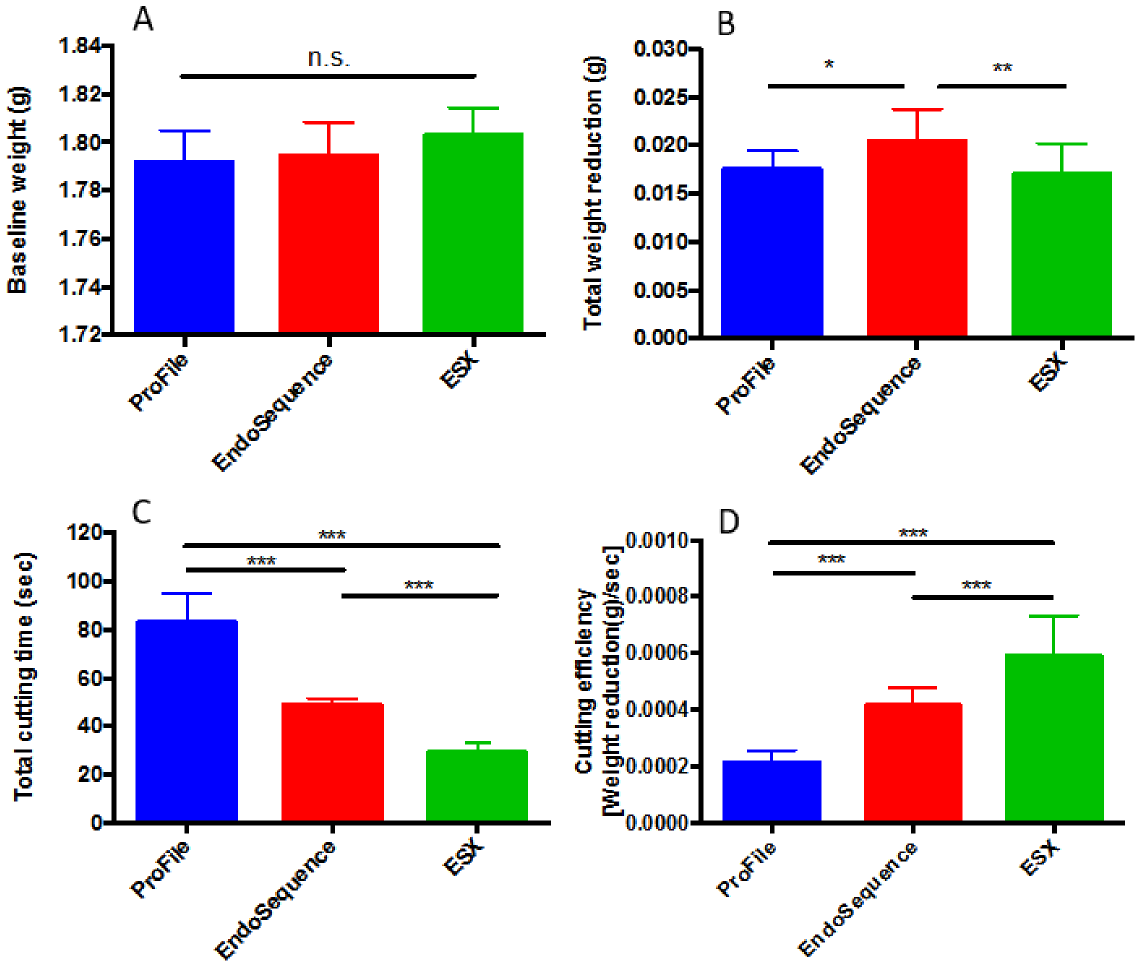

Figure 2. Intergroup comparisons (mean ± SD). (A) Baseline weight; (B) Total weight reduction; (C) Total cutting time; and (D) Cutting efficiency. n.s., not significant; *: $p<0.05$; **:$p<0.01$; ***:$p<0.0001$;

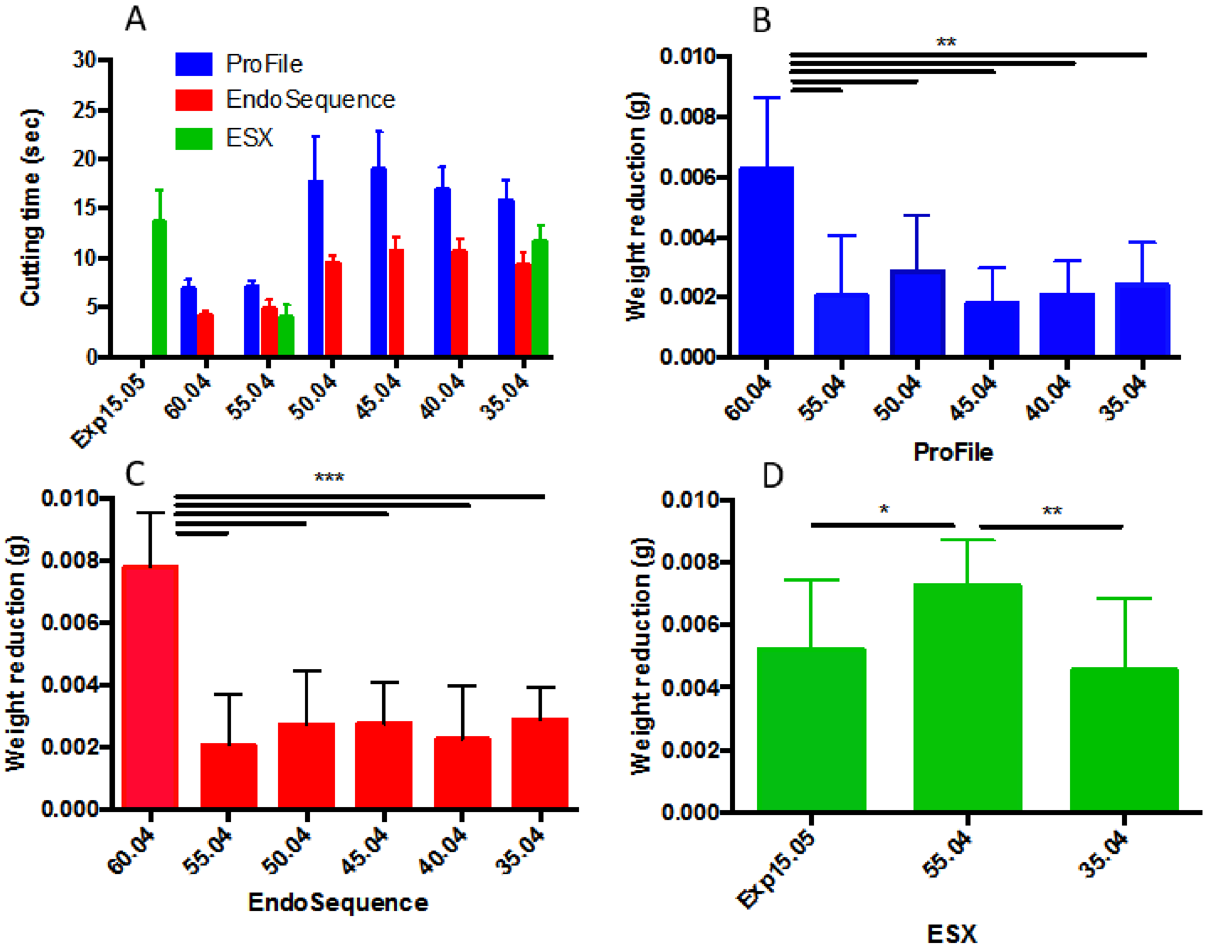

Figure 3. Intragroup comparisons (mean ± SD). (A) Cutting time by file type; (B-D) Weight reduction by file type for (B) Profile, (C) EndoSequence, and (D) ESX. *: $p<0.05$; **:$p<0.01$; ***:$p<0.0001$

CHAPTER 4. DISCUSSION

This study compared the cutting efficiency of three conventional nickel-titanium rotary systems by utilizing a novel model, the TrueTooth replica. The main finding of this study was that ESX rotary instruments demonstrated significantly greater cutting efficiency as compared with the EndoSequence and ProFile systems.

Cross-sectional geometry. The cutting efficiency of a rotary file is dependent on several interconnected parameters, but primarily the result of its cross-sectional design when the taper and technique are the same (5). The cross-sectional design takes into consideration the angle of incidence of the blade and the width of any radial land. In the present study, despite all three rotary systems having a taper of 0.04 and used in a crown down approach, the EndoSequence and ESX, both non-landed instruments with a negative rake angle, demonstrated superior cutting efficiency compared to the ProFile system, which is landed and fabricated with a neutral rake angle. These results are in accordance with other studies (13, 19, 31) where it has been shown that triangular root canal instruments demonstrate superior cutting efficiency compared to those with different cross-sectional geometry. It has been speculated that triangular rotary instruments have sharper edges which create a shaving action that can more efficiently remove dentin (32).

Electropolishing. The electropolished surface of the EndoSequence and ESX instruments may have also played a role in their enhanced cutting efficiency. It has been purported that electropolishing eliminates surface imperfections, optimizes mechanical properties, and increases file sharpness (18, 33). However, Bui *et al.* measured file advancement into plastic blocks and concluded that although electropolishing did reduce resistance to cyclic fatigue it did not significantly affect cutting efficiency (34). The process of electropolishing primarily removes surface projections, which actually elicits a smoothing effect, as opposed to sharpening, and was apparent under SEM imaging (Figure 1). This finding is contradictory to the manufacturer's claims.

Speed. Rotational speed can influence the mechanical properties of nickel titanium instruments (35, 36) as well as cutting efficiency (37). Morgental *et al.* (36) determined that an increased rotational speed of coronal flaring instruments improved cutting ability in both acrylic and dentin substrates. In the present study, an increased speed also allowed for greater cutting efficiency as both the EndoSequence and ESX systems were operated at 500 rpm as opposed to 300 rpm for the ProFile.

Booster tip and cutting efficiency. The ESX system demonstrated significantly greater cutting efficiency than its predecessor, EndoSequence. The 'booster tip', with a more stream-lined configuration and double the cutting edges within the first millimeter of the file, is the only perceived structural difference in the ESX system as compared to the EndoSequence system (Figure 1). Thus, it could be assumed to be the main feature that facilitated canal negotiation and enhanced cutting efficiency. Moreover, the ESX rotary system employed fewer files during mechanical instrumentation. If considered in a clinical setting, where time would be required to change instruments, fewer instruments could possibly translate into further improvement in overall efficiency.

Expeditor files. An Expeditor file is intended to be the primary rotary instrument with both the EndoSequence and ESX systems. The instrument's main purpose is to gauge the canal and aid in the determination of final apical size. However, the Expeditors for the two systems differ in terms of tip and taper, resulting in different shaping effects. The EndoSequence Expeditor (27.04) acts as both a gauging instrument and an orifice shaper, and was thus not included in the study proper. The more conservative ESX Expeditor (15.05) does not coronally flare while gauging the canal. Instead, it creates a specifically sized glide path required for the ESX system necessitating its incorporation into the study's instrumentation protocol.

File measurement. Although all files used in the study fell within the recommended ISO tolerance limits, a trend was observed whereby the EndoSequence and ESX files tended to yield smaller measurements than their ProFile counterparts. This may be a true observation as both the EndoSequence and ESX files undergo electropolishing after being machined. Electropolishing involves the immersion of files into a highly ionic solution in combination with an electric current, which removes a thin outer layer of the instrument (33). However, both the EndoSequence and ESX systems depict alternating contact points that allow for an asymmetrical rotary motion and may possibly compensate for a smaller file size. Conceivably, a smaller instrument undergoing asymmetrical rotation could prepare a canal space of similar dimensions as compared to a larger instrument undergoing symmetrical rotation, such as the case with ProFile instruments. However, the trend of smaller measurements associated with the EndoSequence and ESX systems may be alternatively attributed to the inherent difficulty in measuring triangular instruments with a decreased pitch.

Dentin versus plastic. Using natural teeth presents challenges due to inherent variations within and between teeth. For example, hardness and water content have been described as two predominant variables in dentin samples that make it difficult to compare results from tooth to tooth (25, 30). Stenman (38) has been credited with introducing the use of polymethyl methacrylate as a testing substrate. The plastic was not necessarily found to be an ideal dentin replacement, but the material could perform in a consistent manner in terms of hardness and dimensional stability. Thus, it is believed by some that resin material lends itself to the evaluation of cutting efficiency, serving as a reliable test material (39). However, the lack of a true smear layer being created with the instrumentation of plastic may have an impact on cutting efficiency and requires further investigation.

Advantages of the TrueTooth replica. The advantages of utilizing the TrueTooth replica as an experimental model relate to its anatomically challenging canal configuration providing clinically relevant demands to instrumentation, and fabrication standardization attributed to a 3D printing process having a resolution of 16 micrometers. Standardization of the TrueTooth replica was evaluated in this study by measuring both pre-access and pre-instrumentation weight. Although there were minor variances in the pre-access and pre-instrumentation weights of the replicas, an overall consistency was found. According to Dental Education Laboratories the slight variance in weight is due to post-processing surface treatments as opposed to the 3D printing process itself. Post-processing treatments include the use of sodium hydroxide to remove residual supporting medium, the material in which the replicas are made, and rock tumbling which polishes the external surface.

Limitations of the TrueTooth replica. Conversely, the use of the TrueTooth replica may be viewed as a limitation as it is not a true dentin model. Plastic does not exhibit the same physical properties as dentin being softer and thus easier to cut. According to the manufacturer, the engineered resin polymer in which the TrueTooth is fabricated has a level of hardness approaching that of dentin, yielding a shore hardness value of D83-86 as compared to approximately D90 for dentin (personal communication with Dental Education Laboratories). Thus, development of a man-made material with properties such as hardness and elasticity similar to those of dentin has been suggested for future research (40).

Learning curve with TrueTooth replica. Instrumentation of the TrueTooth replicas proved to be clinically challenging. Canal curvature and constriction, in combination with a slightly softer consistency than dentin, demanded an exacting technique. Despite familiarity with the ProFile system, it was observed that use of the ProFile rotary instruments with the TrueTooth replica required a steeper learning curve as compared to the other file systems (Table 6A). This may be attributable to the neutral rake angle and smaller chip space associated with the ProFile system, resulting in a planning - as opposed to shaving - action exerted on the TrueTooth material. Future studies need to take into consideration the variable difficulty involved in utilizing the TrueTooth replica with different rotary systems.

Canal debridement. It is widely recognized that bacteria cause apical periodontitis (41-43). Irrigation of the canal system is critical to achieving effective debridement and eliminating microorganisms (1, 2), particularly as rotary instrumentation may not reach all surfaces of the canal system (10). From a clinical perspective, the decreased instrumentation time provided by more efficient rotary systems may shorten the time of exposure to antimicrobials. A consideration for more stringent antimicrobial irrigation protocols may be required with such rotary instruments.

Clinical relevance. Finally, although statistical significance in cutting efficiency was found between the three rotary file systems, it remains to be determined whether this would have any effect on clinical outcome. Despite the extensive marketing strategies used to promote nickel-titanium instruments, no conclusions can be drawn from the scientific literature that the design features of any instrument system will provide increased clinical success in canal shaping. Instrument selection should therefore be based on the ability to safely prepare canals, which is founded on a general understanding of design concepts, rather than for perceived benefits in canal instrumentation.

CHAPTER 5. SUMMARY AND CONCLUSIONS

1. This study used the TrueTooth replica as a novel model to evaluate the cutting efficiency of intracanal rotary instruments. **Within the limitations of the study, cutting efficiency was shown to be significantly greater for the ESX rotary system as compared to both EndoSequence and ProFile.** Conversely, cutting efficiency was shown to be significantly less for the ProFile system as compared to both the ESX and EndoSequence.

   Further research is required for the ESX rotary system, as there may be negative consequences to the use of fewer instruments with an increased cutting efficiency. Consideration needs to be made for the file system's ability to remain centered within the canal space or tendency towards canal transportation. An additional concern may be the more narrow 'booster tip'. With less bulk material at the tip of ESX files, there may be a predilection towards instrument separation.

2. **All rotary files used in the study conformed to ISO 3630-1 standards** with regard to cross-sectional diameter and taper. Ensuring instrument adherence to ISO standards is not a common practice in current endodontic studies. Considering the potential impact of file size on mechanical and physical properties, perhaps its evaluation and measurement ought to be considered a core component in instrumentation research.

3. **The TrueTooth replica was found to be a standardized and clinically relevant model for the testing of endodontic instrumentation.**

   Further improvement in the hardness of the resin polymer may limit the perceived tendency to ledge during instrumentation, and thus recapitulate the characteristics of dentin more closely. Additionally, an ability to mount the replicas within dentoforms in a reproducible way would further enhance their clinical applicability. Unfortunately, the use of such standardized testing modalities is not prevalent in endodontics. Future use of this model may potentially further our knowledge of the mechanical properties of nickel-titanium rotary files during intracanal operation.

REFERENCES

1. Bystrom A, Sundqvist G. Bacteriologic evaluation of the efficacy of mechanical root canal instrumentation in endodontic therapy. Scand J Dent Res 1981;89(4):321-328.
2. Dalton BC, Orstavik D, Phillips C, Pettiette M, Trope M. Bacterial reduction with nickel-titanium rotary instrumentation. J Endod 1998;24(11):763-767.
3. Schilder H. Cleaning and shaping the root canal. Dent Clin North Am 1974;18(2):269-296.
4. Buchanan L. Cleaning and shaping the root canal system. Pathways of the pulp 1991;5.
5. McSpadden, J. Mastering Endodontic Instrumentation. In. Chattanooga, TN: Cloudland Institute 2007. p. 67-79.
6. Tucker DM, Wenckus CS, Bentkover SK. Canal wall planning by engine-driven nickel-titanium instruments, compared with stainless-steel hand instrumentation. J Endod 1997;23(3):170-173.
7. Luiten DJ, Morgan LA, Baugartner JC, Marshall JG. A comparison of four instrumentation echniques on apical canal transportation. J Endod 1995;21(1):26-32.
8. Esposito PT, Cunningham CJ. A comparison of canal preparation with nickel-titanium and stainless steel instruments. J Endod 1995;21(4):173-176.
9. Short JA, Morgan LA, Baumgartner JC. A comparison of canal centering ability of four instrumentation techniques. J Endod 1997;23(8):503-507.
10. Peters OA. Current challenges and concepts in the preparation of root canal systems: a review. J Endod 2004;30(8):559-567.
11. Vinothkumar TS, Miglani R, Lakshminarayananan L. Influence of deep dry cryogenic treatment on cutting efficiency and wear resistance of nickel-titanium rotary endodontic instruments. J Endod 2007;33(11):1355-1358.
12. Schafer E, Oitzinger M. Cutting efficiency of five different types of rotary nickel-titanium instruments. J Endod 2008;34(2):198-200.
13. Felt RA, Moser JB, Heuer MA. Flute design of endodontic instruments: its influence on cutting efficiency. J Endod 1982;8(6):253-259.
14. Schafer E. Relationship between design features of endodontic instruments and their properties. Part 1. Cutting efficiency. Journal of Endodontics 1999;25(1):52-55.
15. Wildey WL, Senia ES, Montgomery S. Another look at root canal instrumentation. Oral Surgery, Oral Medicine, Oral Pathology 1992;74(4):499-507.
16. Miserendino LJ, Brantley WA, Walia HD, Gerstein H. Cutting efficiency of endodontic hand instruments. Part 4. Comparison of hybrid and traditional instrument designs. J Endod 1988;14(9):451-454.
17. Rapisarda E, Bonaccorso A, Tripi TR, Fragalk I, Condorelli GG. The effect of surface treatments of nickel-titanium files on wear and cutting efficiency. Oral Surg Oral Med Oral Pathol Oral Radiol Endod 2000;89(3):363-368.
18. Kurtzman GM. Simplifying endodontics with endosequence rotary instrumentation. J Calif Dent Assoc 2007;35(9):625-628.
19. Villalobos RL, Moser JB, Heuer MA. A method to determine the cutting efficiency of root canal instruments in rotary motion. J Endod 1980;6(8):667-671.
20. Bergmans L, Van Cleynenbreugel J, Wevers M, Lambrechts P. Mechanical root canal preparation with NiTi rotary instruments: rationale, performance and safety. Status report for the American Journal of Dentistry. Am J Dent 2001;14(5):324-333.

21. Morrison SW, Newton CW, Brown CE. The effects of steam sterilization and usage on cutting efficiency of endodontic instruments. Journal of Endodontics;15(9):427-431.
22. Fayyad DM, Elhakim Elgendy AA. Cutting efficiency of twisted versus machined nickel-titanium endodontic files. J Endod 2011;37(8):1143-1146.
23. Webber J, Moser JB, Heuer MA. A method to determine the cutting efficiency of root canal instruments in linear motion. J Endod 1980;6(11):829-834.
24. Wan J, Rasimick BJ, Musikant BL, Deutsch AS. Cutting efficiency of 3 different instrument designs used in reciprocation. Oral Surg Oral Med Oral Pathol Oral Radiol Endod 2010;109(5):e82-85.
25. Haikel Y, Serfaty R, Lwin TT, Allemann C. Measurement of the cutting efficiency of endodontic instruments: a new concept. J Endod 1996;22(12):651-656.
26. Plotino G, Giansiracusa Rubini A, Grande NM, Testarelli L, Gambarini G. Cutting efficiency of Reciproc and waveOne reciprocating instruments. J Endod 2014;40(8):1228-1230.
27. Burklein S, Benten S, Schafer E. Shaping ability of different single-file systems in severely curved root canals of extracted teeth. Int Endod J 2013;46(6):590-597.
28. Peixoto IF, Pereira ES, Aun DP, Buono VT, Bahia MG. Constant Insertion Rate Methodology for Measuring Torque and Apical Force in 3 Nickel-Titanium Instruments with Different Cross-sectional Designs. J Endod 2015;41(9):1540-1544.
29. Loizides AL, Kakavetsos VD, Tzanetakis GN, Kontakiotis EG, Eliades G. A comparative study of the effects of two nickel-titanium preparation techniques on root canal geometry assessed by microcomputed tomography. J Endod 2007;33(12):1455-1459.
30. Shen Y, Haapasalo M. Three-dimensional analysis of cutting behavior of nickel-titanium rotary instruments by microcomputed tomography. J Endod 2008;34(5):606-610.
31. Oliet S, Sorin SM. Cutting efficiency of endodontic reamers. Oral Surg Oral Med Oral Pathol 1973;36(2):243-252.
32. Heuer MA. A study of the structural, dimensional and physical characteristics of root canal instruments. Ann Arbor, MI: University of Michigan; 1959.
33. Pohl M, Heßing C, Frenzel J. Electrolytic processing of NiTi shape memory alloys. Materials Science and Engineering: A 2004;378(1):191-199.
34. Bui TB, Mitchell JC, Baumgartner JC. Effect of electropolishing ProFile nickel-titanium rotary instruments on cyclic fatigue resistance, torsional resistance, and cutting efficiency. J Endod 2008;34(2):190-193.
35. Yared GM BDF, Machtou P. Influence of rotational speed, torque and operator's proficiency on ProFile failures. Int Endod J 2001;34(1):47-53.
36. Lopes HP, Ferreira AA, Elias CN, Moreira EJ, de Oliveira JC, Siqueira JF, Jr. Influence of rotational speed on the cyclic fatigue of rotary nickel-titanium endodontic instruments. J Endod 2009;35(7):1013-1016.
37. Morgental RD, Vier-Pelisser FV, Kopper PMP, de Figueiredo JAP, Peters OA. Cutting Efficiency of Conventional and Martensitic Nickel-Titanium Instruments for Coronal Flaring. Journal of Endodontics 2013;39(12):1634-1638.
38. Stenman E. Effects of sterilization and endodontic medicaments on mechanical properties of root canal instruments. Umeå, Sweden: Department of Dental Technology, University of Umeå; 1977.
39. Neal RG, Craig RG, Powers JM. Cutting ability of K type endodontic files. J Endod 1983;9(2):52-57.
40. Stenman E, Spangberg LS. Machining efficiency of endodontic files: a new methodology. J Endod 1990;16(4):151-157.

41. Kakehashi S, Stanley HR, Fitzgerald RJ. The Effects of Surgical Exposures of Dental Pulps in Germ-Free and Conventional Laboratory Rats. Oral Surg Oral Med Oral Pathol 1965;20:340-349.
42. Sundqvist G. Bacteriological studies of necrotic dental pulps. Umeå, Sweden: School of Dentistry, University of Umeå; 1976.
43. Moller AJ, Fabricius L, Dahlen G, Ohman AE, Heyden G. Influence on periapical tissues of indigenous oral bacteria and necrotic pulp tissue in monkeys. Scand J Dent Res 1981;89(6):475-484.

APPENDICES

Appendix 1. Pilot study raw data

Files	Expected file sizes			ProFile Pilot with OS 20/05					EndoSequence Pilot with Exp 27/04					ESX Pilot with Exp 15.05				
os/exp file d3 (mm)	0.35	0.39	0.30	0.36	0.37	0.36	0.36	0.36	0.39	0.39	0.39	0.41	0.40	0.32	0.31	0.32	0.31	0.30
60.04 d3	0.72	0.69	0.75	0.75	0.72	0.75	0.75	0.72	0.73	0.73	0.71	0.73	0.70					
55.04 d3	0.67	0.64	0.70	0.68	0.69	0.67	0.68	0.68	0.69	0.68	0.68	0.69	0.67	0.69	0.67	0.69	0.67	0.69
50.04 d3	0.62	0.59	0.65	0.63	0.64	0.63	0.62	0.63	0.61	0.64	0.63	0.62	0.61					
45.04 d3	0.57	0.54	0.60	0.59	0.57	0.58	0.58	0.59	0.59	0.58	0.56	0.59	0.59					
40.04 d3	0.52	0.49	0.55	0.51	0.55	0.52	0.54	0.52	0.51	0.54	0.53	0.53	0.51					
35.04 d3	0.47	0.44	0.50	0.49	0.47	0.50	0.50	0.50	0.48	0.48	0.49	0.48	0.49	0.48	0.47	0.46	0.47	0.48
os/exp file d13 (mm)	0.65	0.79	0.80	0.67					0.77	0.76	0.77	0.80	0.78	0.78	0.78	0.79	0.78	0.78
60.04 d13	1.12	1.09	1.15	1.13	1.11	1.09	1.12	1.10	1.10	1.12	1.11	1.10	1.13					
55.04 d13	1.07	1.04	1.10	1.06	1.10	1.03	1.07	1.08	1.07	1.06	1.05	1.09	1.06	1.05	1.06	1.06	1.06	1.07
50.04 d13	1.02	0.99	1.05	1.05	1.01	1.01	1.00	1.03	1.00	1.02	0.99	1.01	1.01					
45.04 d13	0.97	0.94	1.00	1.00	0.99	0.97	0.98	0.99	0.96	0.96	0.92	0.97	0.97					
40.04 d13	0.92	0.89	0.95	0.90	0.93	0.93	0.92	0.91	0.90	0.90	0.90	0.90	0.91					
35.04 d13	0.87	0.84	0.90	0.87	0.85	0.87	0.88	0.87	0.87	0.86	0.86	0.87	0.85	0.88	0.85	0.87	0.86	0.86
start mass (g)				1.8280	1.8394	1.8095	1.8169	1.7922	1.7995	1.7846	1.7815	1.7863	1.8056	1.7954	1.8189	1.8062	1.8096	1.8106
os/exp mass									1.7977	1.7824	1.7778	1.7831	1.8045	1.7911	1.8094	1.8028	1.8018	1.8067
60.04 mass				1.8215	1.8317	1.8062	1.8189	1.7902	1.7912	1.7711	1.7715	1.7763	1.7956					
55.04 mass				1.8214	1.8295	1.8043	1.8162	1.7887	1.7882	1.7700	1.7694	1.7745	1.7936	1.7836	1.8048	1.7955	1.7945	1.7978
50.04 mass				1.8212	1.8289	1.8018	1.8133	1.7884	1.7851	1.7666	1.7672	1.7723	1.7908					
45.04 mass				1.8191	1.8264	1.8003	1.8128	1.7866	1.7802	1.7650	1.7636	1.7680	1.7884					
40.04 mass				1.8191	1.8256	1.7996	1.8123	1.7854	1.7782	1.7630	1.7635	1.7658	1.7857					
35.04 mass				1.8180	1.8233	1.7982	1.8114	1.7836	1.7734	1.7611	1.7589	1.7640	1.7808	1.7773	1.8007	1.7916	1.7888	1.7940
os/exp time (s)									8.80	6.64	7.72	6.17	5.82	17.81	16.63	19.56	12.11	18.55
60.04 time				8.30	8.23	7.76	7.50	7.96	4.07	3.54	3.44	2.18	2.18					
55.05 time				8.45	8.07	9.86	5.98	7.44	5.17	4.60	4.45	4.58	3.86	8.05	6.62	2.82	2.65	4.20
50.04 time				20.03	19.13	20.69	23.11	20.96	8.71	7.59	6.87	8.01	7.67					
45.04 time				29.13	30.11	21.27	20.50	17.63	9.76	9.04	8.43	8.84	9.50					
40.04 time				22.77	23.26	20.01	18.40	16.93	9.43	11.46	8.25	9.43	9.95					
35.04 time				18.36	19.65	20.20	20.49	27.85	9.75	10.13	7.99	8.13	10.71	12.44	11.40	9.98	9.89	7.10

Appendix 2. Sample size calculation

Probability of type I error (α)	0.05
Power (1-β)	0.8
Number of groups used in analysis	3
Largest difference between any 2 means	1
Expected background standard deviation	1
Sample size required (per group)	15

Appendix 3. Post-hoc power analysis

Probability of type I error (α)	0.05
Sample size per group used	15
Number of groups used in analysis	3
Observed largest difference between any 2 means	0.0002
Observed residual standard deviation	0.0001
Power calculation	0.9999

The Oregon Health & Science University School of Dentistry
Master of Science in Endodontology Data Sheet

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Exact Title of Thesis:

Cutting Efficiency of ESX, EndoSequence, and ProFile Instruments using the TrueTooth Replica

Special Field of the Thesis:

Cutting efficiency of endodontic instruments

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Brief Summary of Thesis:

An in vitro study using the TrueTooth replica as a standardized model to evaluate and compare the cutting efficiency of three intracanal rotary instruments. Cutting efficiency was found to be significantly greater for the ESX system as compared to both EndoSequence and ProFile systems. All instruments adhered to ISO standards.