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The Evaluation of the Cutting Efficiency of Nickel-Titanium Rotary Files: A New In-Vitro Dentin Model

Brian Papworth

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The Evaluation of the Cutting Efficiency of Nickel-Titanium Rotary Files

A New In-Vitro Dentin Model

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B.B.A., Texas Tech University, 1988
D.D.S., Creighton University, 1992

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Master of Dental Science Thesis

The Evaluation of Nickel-Titanium Rotary Instrument Mechanical Properties

A New In-Vitro Dentin Model

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# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Introduction</td>
<td>1</td>
</tr>
<tr>
<td>Review of Literature</td>
<td>2</td>
</tr>
<tr>
<td>Statement of Problems</td>
<td>18</td>
</tr>
<tr>
<td>Objectives</td>
<td>19</td>
</tr>
<tr>
<td>Study Outline</td>
<td>20</td>
</tr>
<tr>
<td>Part 1. The Standardized Model</td>
<td>21</td>
</tr>
<tr>
<td>Part 2. Pilot Experimentation</td>
<td>27</td>
</tr>
<tr>
<td>Discussion</td>
<td>32</td>
</tr>
<tr>
<td>Figures</td>
<td>36</td>
</tr>
<tr>
<td>Tables</td>
<td>52</td>
</tr>
<tr>
<td>References</td>
<td>56</td>
</tr>
</tbody>
</table>
LIST OF FIGURES

Figure 1 36
Figure 2 37
Figure 3 38
Figure 4 39
Figure 5 40
Figure 6 41
Figure 7 42
Figure 8 43
Figure 9 44
Figure 10 45
Figure 11 46
Figure 12 47
Figure 13 48
Figure 14 49
Figure 15 50
Figure 16 51

LIST OF TABLES

Table 1 52
Table 2 53
Table 3 54
Table 4 55
Introduction

Endodontic treatment can be a technically challenging and difficult procedure. This is especially true of the task of cleaning and enlarging the root canal. Therefore, new instruments and treatment techniques are continuously being suggested.

There has been an evolution of endodontic instrument development that has been enhanced by the improvement of the manufacturing abilities. Hand files were initially made of carbon steel but later, with improved manufacturing abilities they were made of stainless steel. With the development of nickel-titanium wire for orthodontic purposes, this new alloy was applied to the manufacturing of nickel-titanium hand files in endodontics. In recent years, a wide variety of nickel-titanium rotary file systems have been developed.
Review of literature

Originally, the process of instrumenting the root canal consisted of using small handmade steel files for debridement of the diseased pulp tissue. The Kerr Company introduced the first commercially available root canal file in 1915 [1]. It was in principle a twisted steel blank with a triangular or squared cross section. This created an instrument with abrasive surface. The Hedström file was introduced some years later [2]. These files have a much sharper flutes and are capable of more aggressive removal of dentin. The Kerr and Hedström files were initially made of carbon steel but when technically feasible they were later fabricated in stainless steel. In order to enhance the quality and speed of root canal instrumentation several attempts were made to use the traditional Kerr and Hedström files in rotary function. This was however difficult as any of the instruments have flutes in continuous helical arrangements. These flutes easily engaged the root canal walls with the result that the file broke after being locked into position. Due to the stiffness of steel the rotating steel files easily perforated curved root canals. An attempt to circumvent the problems with rotation was the mechanical devices that moved the file in vertical reciprocal movements. This instrument was manufactured by Cardex and marketed as the Racer hand piece. This hand piece accepted conventional short handled reamers and files and removed dentin by oscillating in a vertical plane [3]. Although fractures due to engagements were reduced, the reciprocal movements tended to pack root canal contents out into the periapical tissues [4].

To eliminate the problems with true rotation and vertical reciprocal movements a device with reciprocal rotational movements was introduced. In 1964
Micro-Mega, Medidenta developed the Giromatic hand piece [3]. This system provided a quarter turn reciprocal movement of the instruments used. Commonly used instruments were special rasps and barbed broaches. K-type and H-type instruments were also used. One of the first to investigate this automated hand piece was Frank [5]. He suggested it become a part of the standard endodontic equipment. Like Frank, Weisz found favorable success using the Giromatic [6]. Many studies followed however, that demonstrated less than favorable results with its use [7-9]. These studies found the hand piece to created ledges or zips and altered canal shape significantly. They also found that the hand piece had a tendency to push material out of the apex. Due to its function, the Giromatic hand piece is inherently an ineffective instrument. Therefore, it has not become an important addition to the endodontic armamentarium.

The first bur-type engine driven intra-canal rotary instruments of some importance were Gates Glidden (GG) burs and Peeso reamers. These instruments are used with a slow-speed hand piece. The GG bur is primarily used during initial root canal preparation to open the orifices and the coronal aspect of the root canal preparation. The risk for perforation with GG burs is less than with other types of burs because the short head is less self-guiding. However, it is self-centering in the root canal. This can result in unexpected thinning of the furcation wall of root canals when the larger sizes are used. This is especially true on the furcation sides of mesial roots of molars.
The Peeso reamer is an instrument primarily used for post space preparation. Due to the instrument stiffness, it does not follow the root canal if there is a slight curvature. This reamer cuts laterally therefore; it is subject to causing root perforations despite a “safety tip” design.

In the early 1960’s W.F. Buehler at the Naval Ordinance Laboratory in Silver Springs, Maryland, USA developed a nickel-titanium alloy [10]. This alloy was given the name Nitinol [10]. Several years later Buehler evaluated the metallurgical properties and found that nitinol is an equiatomic intermetallic compound that has the unique property of shape memory and super-elasticity. These properties are the result of a transition in crystal structure (electron shift) that occurs by deformation and cooling. Upon reversing the transition by heating, the structure reverts to its higher temperature form, accompanied by abrupt property changes that are reversible [11]. Therefore, when nitinol wire is subjected to a load, the wire will return to its original shape when the load is removed [12]. In addition, Nitinol alloy has been shown to have greater strength and a lower modulus of elasticity compared with stainless steel [13, 14]. The use of stainless steel hand files in curved canals can result in undesirable changes in the canal shape [15]. The use of nickel-titanium instruments may reduce the procedural errors during the instrumentation of curved root canals [16].

In 1988 Walia et al. [16] fabricated a file made from nickel-titanium alloy. Due to the very high flexibility and alloy memory, conventional techniques to fabricate K-type file by twisting was not feasible. Instead, thanks to improved metal grinding techniques and computer assisted machining techniques, it was now possible to grind out instruments from nickel-titanium wire. Hand files of K and H designs were very soon
manufactured. Although very useful in curved root canals for reaming the canal space the instruments were less useful for bulk dentin removal due to the lack of stiffness. Therefore, these new hand instruments were not universally accepted.

The experience with the nickel-titanium hand instruments very soon led to the development of rotary instruments. The major entries to the commercial market were the NT Company with McXIM®, LightSpeed Technology with the LightSpeed® instrument, and Tulsa Dental with the ProFile 29® instrument.

The design of rotary endodontic file systems encompasses many variables. Although appearing different, the initial instruments all had similar design features. The most important issue was the lack of an aggressive rake angle. During the development of hand files the initially common negative rake angle was slowly changed to a neutral position. In the years leading up to the rotary nickel-titanium instruments many H-type files had slightly positive rake angles.

The new rotary nickel-titanium instruments all were designed with neutral rake angles. The theory behind this design feature was that aggressive rake would engage the instruments resulting in a high rate of breakage.

Other differences between the new instruments were different designs of blades, grooves and instrument tip. A new concept in the early instrument was the use of “lands”. The instruments were machined out of a conical smooth blank. Three spiral U-like grooves were ground in a helical pattern from these blanks. The areas between the grooves were left unmachined and therefore maintained the diameter of the blank. These blank areas spiraling along the instrument were called ‘land’.
The theory behind this design was that the lands were to keep the instrument centered in the canal. The angle between the groove and the land was the abrading surface with a negative or neutral rake.

These early instrument designs have been significantly improved during the evolution of these instruments and at this time it is possible to identify three generations of different instrument designs.

**Generation I.**

Initially there were three instruments commercially available. They were McXIM®, LightSpeed®, and ProSeries 29®.

The McXIM®

The McXIM® rotary files, designed by Dr. McSpadden, were made by NT Company and were designed to be a supplement to the NT Engine® files. The NT engine files had a standard 0.02mm/mm taper. The file design varied with the instrument size, with instruments of smaller sized having an H-type design with diminutive radial lands, while the larger sizes had a unique, dissimilar helical angle and spacing in order to prevent binding. The McXIM® series incorporates a range of six files with tapers increasing from 0.02 mm/mm to 0.055 mm/mm. They all have a tip size of a 0.25 mm. The 0.02, 0.045, and 0.055 mm/mm taper instruments were of a U-file design while the other two tapers were of H-design. The combination of the NT engine files and the McXIM® instruments were prescribed to be used in a special order. The procedures were complex. [17].
Lightspeed®

The LightSpeed nickel-titanium rotary instrument was derived from an earlier hand instrument called the Canal Master [18]. The Canal Master was later manufactured in nickel-titanium alloy providing increased flexibility [19]. Although the stainless steel Canal Master had mixed reception [20] the nickel-titanium Canal Master was a clear improvement [21].

The development of the LightSpeed® system originated with the Canal Master U hand file which was made of nickel-titanium. The LightSpeed® system consists of 22 instruments of ISO-like sizing between 0.20 mm and 1.40 mm. The sizes between 0.20 mm and 0.70 mm where in steps of 0.05 mm after which the sizes increased with 0.10 mm to 1.40 mm. The instruments have a flexible, nontapered 16-mm shaft, short cutting heads with blades of a U-file design with a neutral rake angle, and a noncutting pilot. The length of the cutting head of the pilot tip varies with instrument size, the smallest head being 1 mm in length. The instruments when properly used prepares the root canals in a circular and controlled fashion [22].

At this time, the LightSpeed® system is the only instrument that has not undergone any significant changes and is still extensively marketed.

ProFile Series 29®

ProFile® nickel-titanium rotary instruments were first introduced as the ProFile Series 29® by Tulsa Dental. These instruments have three helical, equally spaced U-shaped grooves around the shaft of a tapered nickel-titanium wire with a neutral rake
angle, and a noncutting tip. The area of ungrounded shaft, the radial lands, allows greater accuracy of measurement in manufacturing. Thus, the tolerance can be as low as ± 0.003-mm as opposed to the usual ISO required tolerance of ± 0.02-mm for hand files [23].

This original series consisted of nine instruments numbered 1 through 10. Unlike the ISO standard of 0.05 or 0.1 mm increase in diameter; the ProSeries 29® increased in diameter by a consistent 29 percent. The size increase between the first two instruments is comparable to the ISO standards while there was a much greater incremental increase in size with the larger instrument. The available tapers are 0.04 mm/mm, 0.06 mm/mm, and 0.08 mm/mm [24].

**Generation II.**

After the initial presentation of several types of rotary nickel-titanium instruments there was a period of reconsideration and development based on empirical observations.

**ProFile®**

The ProFile Series 29® was followed by a ProFile® (Dentsply Tulsa Dental, Tulsa, OK, USA) instrument with sizes corresponding to the ISO standard which was the dominating way of describing instrument sizes. The available tapers for the ProFile® are 0.02 mm/mm, 0.04 mm/mm, and 0.06 mm/mm. The ProFile® ISO is available in tip sizes starting at 0.20 mm and up.

**ProFile GT™**
ProFile® GT™ (Dentsply Tulsa Dental, Tulsa, OK, USA) instruments are a modification of the original ProFile concept. The standard ProFile® GT™ instrument sequence consisted of four files, all with a tip diameter of 0.20mm. The tapers offered were 0.06 mm/mm, 0.08 mm/mm, 0.10 mm/mm, and 0.12 mm/mm. Recently, the ProFile® GT™ series has added tip sizes 0.30 mm and 0.40 mm a wide selection of tapers of 0.04, 0.06, 0.08, 0.10, and 0.12 mm/mm. The 0.12 taper is now also available in tip sizes 0.35 mm, 0.50 mm, and 0.70 mm.

Quantec®

The original Quantec® 2000 Series (Tycom, Irvine, CA, USA) files had two unequally spaced, wide radial lands, with a reduced peripheral surface ground around the shaft of the nickel-titanium wires. The complete Quantec® 2000 Series instruments consist of ten files. The files vary from 0.02 mm/mm to 0.06 mm/mm taper with tip sizes ranging between 0.15 mm to 0.45 mm. The tip design had four-facets. This instrument was the first to have a slightly positive rake angle. Due to the positive rake angle, maximum cutting efficiency could be achieved resulting in decreased stress on the instrument tip [25].

The Quantec® 2000 Series was recently replaced by two new series based on the tip geometry of the files, the Quantec® LX and the Quantec® SC (Analytic Endodontics, Glendora, CA, USA). The manufacturer describes the LX as a non-cutting tip design that maintains a central axis and deflects around severe curvatures. The SC or safe-cutting tip design is described as a negotiating tip that cuts as it moves apically, following canal pathways and minimizing stress. This series of files is available with the same taper and
tip size as the Quantec® 2000 series. Additionally, the manufacturer introduced the
Quantec® Flare Series. This series is designed to complement the standard Quantec®
tapers by shaping the coronal portion of the canal utilizing files of increasing tapers of
0.08, 0.10, and 0.12 mm/mm with ISO tip sizes of 0.25 mm.

**Generation III**

With the third generation rotary nickel-titanium instruments the land concept was
discontinued. The new instruments were more aggressive with a positive rake angle and
sharpness like a Hedström file. This sharpness decreased the torque forces on the
instruments resulting in less risk for torque fractures. Due to the low torque, the working
rotational speed has been increased to 500-600 rpm. In the first and second generation of
instruments the presence of well-defined lands prevented the instruments from engaging
in the canal and break due to binding. The third generation of nickel-titanium
instruments was designed with variable helical angles and variable distances between
cutting edges. This arrangement prevents the rotary nickel-titanium instrument from
being engaged and fractured.

**Hero 642 ®**

The first instrument introduced in the third generation of instruments is the
Hero 642® (High Elasticity in Rotation) (Prodonta S.A. Micro-Mega Export, Geneva,
Switzerland). These instruments have a trihelical Hedström design that has three equally
spaced rounded cutting blades with a positive rake angle ground into nickel-titanium
shafts leaving a large inner core for improved strength. (Figure) The improved strength is desirable, but this design affects the cutting efficiency. The instrument series consists of three different tapers of 0.02, 0.04, and 0.06 mm/mm for each size 0.20 mm, 0.25 mm, and 0.30 mm. Additional instruments sizes of 0.02 mm/mm taper and sizes up to 0.45 mm are also available [26].

**ProTaper™**

The ProTaper™ (Dentsply Tulsa Dental, Tulsa, OK, USA) file system was recently introduced. This system consists of six triangular cross-section designed files. The first three are shaping files and are designated as SX, S1, and S2. The SX is an orifice opener with a tip size of 0.19 mm and at D14 a diameter of 1.2 mm. The S1 has a tip size of 0.17 mm and at D14 a diameter of 1.2 mm. The S2 has a tip size of 0.20 mm and at D14 a diameter of 1.2 mm as well. The final three files are finishing files and are designated as F1, F2, and F3. The F1 file has a tip size of 0.20 mm and from D0 to D3 a taper of 0.07 mm/mm. The F2 file has a tip size of 0.25 mm and from D0 to D3 a taper of 0.08 mm/mm. The S3 file has a tip size of 0.30 mm and from D0 to D3 a taper of 0.09 mm/mm. From D4 through D14 the three finishing files taper decreases [27].

**RaCe®**

The RaCe® instrument system (Rotary Alternating Cutting Edge) (Brassler USA, Savannah, GA, USA) consists of five files numbered 1 through 5 and with tapers of 0.10 mm/mm through 0.02 mm/mm. The file geometry is a triangular cross-section with two cutting edges and a variable helical angle. The file has one set of sharp cutting edges that
alternate with a second set pitched at a different angle. The alternating cutting edges of
the file constantly switch helix angles of the blades as they rotate inside the canal. The
working length is eight millimeters. File 1 has a tip size of 0.40 mm and the remaining
files have tip sizes of 0.25 mm. A 0.02 mm/mm taper file with a tip size of 0.35 mm is
also available. The manufacturer recommends that the files are used in a crown-down
technique but can be used in a step-back technique as well (Brassler USA, Savannah,
GA, USA, 2001).

Measurements

To understand the behavior and limitations of endodontic rotary instruments,
adequate testing is necessary. No generally accepted method exists for the evaluation of
the mechanical properties of rotary instruments. Presently ADA/ANSI standards exist for
torque resistance and bending for endodontic hand files. Standards for machining
efficiency of hand and rotary instruments are not in place. Because of the differences in
use it is not possible to apply the standardized test methods defined for hand held files.
To apply hand file standards to rotary instruments is a flawed application of these
standards.

Hand files are essentially used in a static mode whereas rotary files are used in a
dynamic mode. This difference is not accounted for when applying established hand file
standards to rotary files. Rotary files are subjected to rotational torque during use and
have not been tested in this manner. Existing standards for torque resistance of hand files
are performed in a static state when subjecting the instrument to torquing forces.
Fatigue of the instrument is another concern for rotary instruments. The limits of the instrument in constant motion have not been established. This is an important mechanical property of the instrument to determine its limitations during use.

With the introduction of rotary instruments researchers have explored many ways to evaluate their mechanical properties. Presently the primary model systems utilized in the literature are clear resin blocks or extracted human teeth. Using these models researchers have attempted to examine the instruments mechanical properties as well as the effects of instrumentation on canal morphology. Another model system utilized bovine bone as a substrate however, its use has not remained popular [28-33]. Other model systems have used glass tubes [34], steel tubes [35], or tempered steel curves [36] to fabricate simulated canals.

The following model systems remain popular methods for the testing of endodontic hand and rotary files.

**Resin block model**

In 1975 a method was developed to fabricate a simulated standardized canal in a clear acrylic resin block to evaluate preparation on canal shape and apical preparation using hand files. The canals were made utilizing a clear polyester casting resin poured into a baseplate wax mold and inserting lubricated #20 silver cones. Upon curing, the silver points were removed leaving a simulated canal space. The clear resin block could then be evaluated for changes in canal shape after instrumentation [15]. This method has also been utilized as an aid in the teaching of canal instrumentation [37].
The use of resin blocks allows one to control the size, shape, and curvature of the simulated canal. However, the resin substrate presents problems with the use of rotary instruments. Kazemi et al. [38] have shown that the wear on nickel-titanium files could not be shown in Plexiglas the same as could be shown on dentin. They speculated that deformation of the file’s machining edges that occurs when used on dentin does not occur when used on Plexiglas. Further studies have shown that plastic substances do not alter the machining efficiency of endodontic files and therefore provide little help in assessing wear resistance [39] [40]. Additionally, the hardness of the resin does not reproduce that of dentin [41].

The endodontic literature illustrates that the use of a resin substrate is not a suitable dentin substitute [38]. The testing of nickel-titanium rotary instruments using a resin substrate will not yield the true machining or wear characteristics of the instrument. Therefore, to understand the mechanical properties of these instruments the proper dentin substrate must be used.

It is possible that the use of a resin substrate to evaluate rotary instruments will generate frictional heat that will melt the resin thereby affecting the instruments cutting efficiency.

**Natural root canals**

Root canals of extracted human teeth have been used in many studies for the evaluation of nickel-titanium rotary systems [42, 43]. Rotational speed and the torque generated during instrumentation were evaluated and parameters regarding use of the instruments used were determined. The wear of nickel-titanium rotary instruments has
also been investigated [44]. In each of these studies the deficiency of standardized testing methods distorts the conclusions regarding clinical use of the respective instruments. Without standardized tests, the implication of the results is in question. The use of extracted human teeth introduces variability of the testing conditions. Root canal systems vary in their size, shape, and curvature [45]. Dentin microhardness has been shown to vary by as much as 25% [46, 47]. The use of extracted human teeth introduce variables that cannot be controlled therefore, standardization of the test system is not possible.

**Bramante segmental model**

Another area of research has investigated the effect of instrumentation on canal shape [48]. This technique was introduced to evaluate the use of hand instruments but has more recently been applied to rotary instruments. Using this technique, Bramante et al. evaluated the canal morphological changes by comparing before and after photographs of prepared canals in extracted human teeth.

Briefly, the tooth was inserted into a colorless acrylic resin and shaped into a pyramidal block. Transverse grooves were then made over the margins of the block, according to the proximal surfaces of the tooth. The block was then placed in a horizontal position and covered with dental plaster. Prior to the plaster setting, grooves were made over its superficial area and guides were obtained. Once the plaster was set, the surface was lubricated; a new layer of plaster stone was poured over the resin block and dental plaster. The plaster stone would serve as a removable muffle system. The resin block, with the root, was removed and sectioned at the cervical, middle, and apical levels. The sectioned portions were then mounted on glass slides and photographs were taken to
obtain transparencies. The sections were then placed in their original positions, placed in the muffle, and the canals instrumented. Again, the sections were removed, photographed, and transparencies were made. The transparencies were then projected with x10 magnification in order to delineate the root canals on a piece of white paper. The tracings were first done for the uninstrumented canal. Following instrumentation, the outline was again traced to allow the superimposition of the canal profiles. This technique allows the comparison of the original root canal shape to that of the instrumented canal shape.

An early study using this technique was done by Gilles and del Rio [20]. They examined the Canal Master and K-type hand files using the Bramante technique to compare canal enlargement of curved canals in extracted human teeth. Using this technique, their study concluded that less transportation of the canal as well as a rounder preparation resulted using the Canal Master files.

Using a modified Bramante technique, Glosson et al. [49] compared K-Flex files, Ni-Ti hand files (Mity files), NT Sensor engine-driven files, Ni-Ti Canal Master "U" hand instruments and Ni-Ti Lightspeed instruments. They found that Engine-driven Ni-Ti instruments (Lightspeed and NT Sensor file) and hand instrumentation with the Canal Master "U" caused significantly less canal transportation, remained more centered in the canal, removed less dentin, and produced rounder canal preparations than K-Flex and Mity files.

This technique has continued to be modified to improve its application by many authors [50-52]. Each of these authors’ modification of Bramante’s system sought to improve its accuracy, usability, and durability. However, each of these systems focus is
comparing the canal shape before and after canal instrumentation. Each of these techniques has been used to assess various endodontic file systems. The use of this type of system does not elicit any information regarding the mechanical properties of the rotary instruments used during instrumentation. Furthermore, each canal will subject the instrument to conditions that are neither identical nor reproducible. Results must be interpreted with caution regarding the true behavior and limits of the tested instruments.
Statement of Problems

The endodontic profession is replete with nickel-titanium rotary systems. These systems are rapidly developed and marketed but are poorly tested or evaluated. In addition, these systems are costly and do not provide all the answers to the difficulties encountered during endodontic treatment. Most of the systems advocate the use of 4 or 5 instruments for the complete preparation of the canal system. This approach will not prepare the apical part of the root canal adequately, especially in a tooth with resorbing apical periodontitis [53].

The absence of adequate testing standards for engine-driven nickel titanium instruments necessitates the study of these instruments’ mechanical properties and the resulting clinical implications. Currently a good way to objectively assess the instruments’ wear and fatigue characteristics does not exist. Without an objective method to evaluate these instruments, the use of any rotary system by the practitioner is done without the knowledge of the instruments’ proper application to case selection and mechanical limitations during instrumentation.
Objectives

The objectives of this study were to design a standardized dentin model for the evaluation of certain aspects of the cutting and machining qualities of nickel-titanium rotary instruments.
Study Outline

With an understanding of the deficiencies of the currently used testing systems, the design of a new testing model needed to address a multitude of testing factors.

The substrate used for testing needs to be similar to human dentin. As previously discussed, the use of plastic or resin does not affect the wear of the instrument. The simulation of wear on a dentin substrate is paramount to understanding the instruments’ limitations.

A technique was sought to measure instrumentation time while controlling the instrumentation conditions. The system must allow instrumentation to be carried out in dry or wet conditions. Therefore the use of canal lubricants must be possible.

A new testing model must evaluate an instrument under repeatable or reproducible experimental conditions. This could only be accomplished with the development of a standard model.

In addition to the need for a dentin substrate, the dentin or canal samples must be standardized. The control of the canal size would overcome the deficiencies of using extracted human teeth.

Finally, the designed test system should allow the control of such instrumentation parameters as the weight applied to the hand piece, rotational speed, and the number, length, and frequency of strokes of the instrument.
Part 1. The Standardized Model

Dentin substrate

Preparation of Dentin

Monoradicular bovine teeth were obtained by extraction from anterior jaw segments. The teeth were debrided of soft tissue and placed in 1% NaOCl for one hour to remove organic remnants. Teeth were then decoronated at the CEJ, pulp tissue removed with a barbed broach, rinsed in saline, and stored in a solution of (0.2%) sodium azide. All specimens were rinsed with saline prior to use.

The mounting of each tooth was facilitated by the use of a surveyor. A surveyor stylus was placed inside the root canal to hold the tooth in a perpendicular plane to the surveyor platform. Plastic molds measuring 25 mm x 25 mm x 25 mm were filled with freshly mixed Coldpac tooth acrylic (The Motoloid Co., Chicago, IL, USA) and the tooth was lowered until it was flush to the CEJ (Figure). After setting, the acrylic block and the mold were marked on the same side with a Sharpie® permanent marker (Newell Rubbermaid, Freeport, IL, USA) for orientation purposes to insure the same position during sample manipulation (Figure). The sample was placed in a Buehler® Isomet™ (Buehler, Lake Bluff, IL, USA) low speed saw equipped with a 102 mm x 0.3 mm Buehler® diamond wafering blade. The blade was positioned to remove 1mm from the coronal aspect of the sample to yield a flat surface perpendicular to the long axis of the tooth for the drilling of the canals (Figure).

Preparation of artificial canals
A canal size of 0.35 mm was selected for the study. To obtain this size canal a carbide drill (Metal Removal Industrial Tooling, Rogers, AR, USA) of 0.35 mm diameter and 5 mm length was used (Figure). An 8-inch drill press with a 1/3 horsepower motor (Sears/Craftsman, Chicago, IL, USA) was used for all canal preparation (Figure). It was decided that a canal of at least 9 or 10 mm length was needed. Therefore, it would be necessary to construct the canal in sections. Initially four canals were drilled in the coronal surface of the sample (Figure). The acrylic block was repositioned in the plastic mold using the alignment markings. The sample and saw were positioned to cut a section 4.3 mm in thickness. This technique allowed pilot holes in the remaining coronal segment that would serve to align the drill for the next section (Figure). This process was repeated yielding three sections of 4 mm in thickness and a canal total length of 12 mm (Figure). All sections were marked to allow for proper orientation. Additionally, all samples were kept moist during the fabrication process.

For the segments assembly straight stainless steel wire of 0.33 mm diameter (Small Parts Inc., Miami Lakes, FL, USA) was placed through the canals to properly align the segments (Figure). Cyanoacrylate (Manco, Inc., Avon, OH, USA) was used to secure the three segments (Figure). During pilot studies it was determined that the segments may separate when placed in the vise for securing the sample during the instrumentation of the canal. To overcome this, the glued segments were secured with machine screws size 0/80 x ½” at two opposite corners of the acrylic mold (Figure). All segments were measured, placed in the low speed saw, and cut from the apical end to a length of 9 mm. During pilot studies, canals greater than 9 mm in length subjected the
instrument to forces exceeding the torque limit of the instrument and resulted in instrument fracture.

**Apparatus**

The speed of the hand piece was controlled by a digital Dentsply Aseptico (Aseptico International, Woodinville, WA, USA) slow-speed, high-torque electric motor that was set at 300 rpm. A Dentsply Aseptico (Aseptico International, Woodinville, WA, USA) Minihead Contrangle 16:1 reduction hand piece was attached to the electric motor and controlled by a rheostat. A computer program controlled the frequency and speed of the cyclical stroke of the file.

The testing device consisted of a platform guided by fixed wheels on a track of 16 inches in height. The platform was equipped with a counterbalance that would allow the control of the load applied to the platform [54]. The platform was fitted with securing screws that would allow the placement and positioning of an electric hand piece (Figure). The hand piece could be adjusted to insure that it was perpendicular to the canal sample. A counterbalance weight of 343 grams was required to offset the weight of the platform and mounted hand piece. During initial testing of the system, a weight of 250 grams was applied. This weight did not provide enough of a load to provide the proper contact with the metal contact bar below the sample. Without enough of a load, when the file tip first contacted the metal plate, the timer would not stop. Weight was added in 25 gram increments until the optimum weight was determined. The final weight was a 365 grams.

To simulate a clinical “pecking” movement, the testing device was equipped with an electric motor with an eccentric movement mounted so that the platform, with the secured
hand piece, would move the instrument in an axial motion allowing the cleaning of the flutes during the outward stroke (Figure). The cyclical axial motion was controlled by computer software that allowed the number and speed of the strokes to be precisely determined. The stroke length, determined by the variable position of the motor, was set so that the stroke length was 11 mm. This stroke length was determined to be sufficient to allow for the height of the 9 mm sample placed on the contact bar which was secured in a vise. This would insure that 1 mm of the file tip would always remain in the canal during the most outward stroke during instrumentation. With this positioning, the length of the stroke was shorter at the beginning of instrumentation and as the file depth increased, the length of the stroke would increase. By adjusting the speed of the motor, the frequency of the strokes could be set to vary between 16-40 strokes per minute.

To calculate the time of instrumentation, the start/stop circuit of an Accusplit® stopwatch with readings of 1/100th second (Accusplit, San Jose, CA, USA) was modified so that when a Root ZX® file clip (J. Morita USA, Inc., Irvine, CA, USA) was attached to the rotating file, and the file contacted a metal contact bar below the sample, the timer would stop (Figure).

During initial testing it was found that the Accusplit® stopwatch was too sensitive and electrical interference would occur causing the premature stopping of the timer. To prevent the electrical interference, the timer was grounded to insure the accuracy of the timing of instrumentation.

Discussion
The use of bovine dentin as a human dentin substitute has been examined by Schilke and co-workers [55, 56]. Schilke et al. found when comparing bovine and human dentin that the number (per mm²) and size of dentin tubules were not significantly different. Studies of the microhardness of human dentin have reported Knoop hardness numbers (KHN) ranging from 20-83 KHN [57, 58]. Knoop hardness numbers of bovine dentin has been found to range from 61-89 KHN [59, 60]. The KHN of bovine dentin shows less variation in hardness as well as being slightly harder than human dentin. Therefore, because of its similarity to human dentin, and acceptance as a human dentin substitute, we chose this as a testing substrate.

The fabrication of artificial canals of predetermined size and shape were introduced by Weine [15]. Numerous studies have been done using a similarly fabricated artificial canal made of various materials to evaluate nickel-titanium rotary files [25, 26, 61-66]. Presently, no one has demonstrated the fabrication of an artificial canal using a dentin substrate.

The dentin samples and artificial canal preparation was carried out to yield standardized canals of 0.35 mm in diameter and of 9 mm in length. Anatomic literature has shown great variation in human molars [45, 67]. Based on these studies, the selection of 0.35 mm for the canal diameter is appropriate. It has also been shown that the average canal length for maxillary and mandibular first and second molars is estimated to be 20.4 mm [1]. Allowing an appropriate length for the clinical crown, the root length can be estimated to be 9 to 10 mm in length and therefore our samples are representative of anatomical root length.
The weight selected for the load applied to the hand piece was 365 grams. This weight is consistent with similar studies that have used weights ranging from 200-550 grams [68, 69].

This process of developing a canal of known length in a suitable substrate will provide a model for the evaluation of instrumentation wear.
Part 2. Pilot Experimentation

General Objectives

The general objective of this study was to develop a machine that could evaluate the effectiveness and wear of nickel-titanium rotary files. Two pilot studies were conducted to validate the use of the apparatus.

A. Effect of irrigation and chelating agents

Objectives

The objectives of this phase of experimentation were to evaluate the effects of saline irrigation and Glyde™ canal lubrication on instrumentation time while controlling the weight applied, speed, and the cyclical axial stroke length of the file.

Materials and Methods

For the instrumentation ProFile® (Dentsply Tulsa Dental, Tulsa, OK, USA) 0.35 mm, 0.04 mm/mm taper, and 25 mm length files were used. Each file was replaced for each new canal during the experiment. The motor controlling the frequency of strokes was set at a rate of 16 strokes per minute. The hand piece motor was set at 300 rpm. The canal conditions selected were three:

1. Dry
2. Glyde™ File Prep Gel (Dentsply Mallefer North America, Tulsa, OK, USA)
3. Saline irrigation

Procedures
Forty-five canals were selected for this part of testing. Fifteen canals were randomly selected for each of the canal conditions tested.

The sample was placed on the contact platform and secured in the vise. The Profile® instrument was placed in the latch type hand piece and the Root ZX® file clip was attached to the file shaft to provide contact circuitry to stop the timer when the file contacted the metal platform below the sample (figure). The file was aligned with the tip of the file resting in the opening of the canal. Instrumentation commenced with the simultaneous starting of the watch and the hand piece.

During instrumentation when the file was at the upward stroke of the cyclical axial motion, compressed air (Kensington Technology Group, San Mateo, CA, USA) was used to remove dentin debris from the file (Figure). This was repeated for each stroke until the timer stopped or if 5 minutes had elapsed. For the saline group, following the air application, a 10 ml Luer-Lok™ syringe (Becton Dickinson & Co., Franklin Lakes, NJ, USA) with a Monoject® 27 gauge needle (Sherwood Medical, St. Louis, MO, USA) was used to apply saline (Figure). For the Glyde™ group, the paste was applied to the tip of a cotton swab was used to wipe the file and remove dentin debris (Figure).

One-way ANOVA and post-hoc Tukey’s test were used to analyze the data.

Results

The mean machining time for the dry, Glyde™, and saline groups were 1.75 ± 1.28, 1.52 ± 0.67 and 1.79 ± 0.88 minutes respectively (p>0.05). Regardless of the test conditions, there were no statistically significant differences between the three test groups.
B. Instrument wear

Objectives

The objectives of this experiment were to evaluate the effect of wear on instrumentation times of repeatedly used files under identical test conditions and to evaluate the effect of canal lubricants during canal instrumentation.

Materials and Methods

For this experiment, thirty ProFile® 0.35 mm, 0.04 mm/mm taper, and 25 mm length files were assigned to the three test groups (Dry, Glyde lubrication, and Saline lubrication). Each group of ten files was tested using identical conditions and testing methods as used during experiment A. The instrumentation time was again recorded or was stopped if 5 minutes elapsed without complete instrumentation of the canal. This procedure was repeated so that each file was used a second time repeating the same conditions and recording the instrumentation time.

McNemar and Fisher’s Exact test were used to analyze the data.

Results

The mean instrumentation times for the first file run for the groups Dry, Glyde, and Saline were 2.03 ± 1.17, 1.99 ± 0.92, and 1.89 ± 1.06 minutes respectively (p<0.05). Instrumentation times for the second file run for the test groups Glyde and Saline was 2.81 ± 1.30 and 2.20 ± 1.02 minutes respectively. Times could not be calculated for the second run dry group because 6 of the 10 files were in excess of five minutes. Comparing
the instrumentation time for first run and second run, only the saline groups demonstrated a significant difference between first and second run instrumentation times.

**Discussion**

The wear of nickel-titanium instruments is presently an area of little research. This problem lies in the reality that there has not been a model system in place to objectively measure the instruments’ wear. This study developed a technique that allows the evaluation of the effect of wear on instrumentation time. The increase in instrumentation time for second run files under identical test conditions indicates that the instruments are less sharp and require additional time to complete the instrumentation of the second canal. This would indicate that with the single use of an instrument, significant wear is occurring and must be considered when determining the number of times an instrument may be used.

This study hypothesizes that an instrumentation time limit of five minutes is sufficient for the purpose of this experiment. Actual clinical use of a single file during instrumentation approximates 5-10 seconds. Therefore, a speed setting of 300 rpm would subject the file to 30-60 revolutions. In this study five minutes of continuous use at 300 rpm would subject each file to 1500 revolutions. Therefore, sufficient time to demonstrate wear would occur in a five minute testing time period.

The goals of irrigation are the lavage of debris, tissue dissolution, anti-bacterial action, and lubrication [70]. In this study saline was used to facilitate the removal of dentin debris and lubricate the canal. It would not have any effect on any remaining organic or inorganic material within the canal.
Nygaard-Østby was the first to suggest the use of EDTA during root canal instrumentation [71]. Our use of Glyde™, which is composed of EDTA (ethylene diamine tetracetic acid) and carbamide peroxide in a water base, would also act as a lubricant as well as breakdown any organic or inorganic contents.

In this study both irrigating agents acted only as a canal lubricant. Because the canals were drilled between the outer root surface and root canal, the simulated canal would not contain any pulp tissue and minimal if any organic debris.
Discussion

The results of this study indicate that the testing apparatus was an effective model to demonstrate the machining wear of nickel-titanium rotary files. The apparatus provides a reproducible technique to instrument a simulated canal while controlling the load applied to the hand piece, the number, length, and frequency of strokes, and the speed of the rotary instrument.

Furthermore, this study indicates that the wear of nickel-titanium rotary instruments is a significant occurrence during the instrumentation of a simulated dentin canal. In the first experiment comparing Dry, Glyde, and Saline groups, our results did not demonstrate a significant difference between the three groups. However, during experiment two it was demonstrated that there was a statistically significant difference between the instrumentation times for the Glyde group for the first and second run of the file. There was no significant difference between the Saline first and second run of the file. Differences could not be calculated for the dry condition group because six of the ten canals were in excess of five minutes during the second run of the file. This study is the first to demonstrate the wear of nickel-titanium rotary files using a dentin substrate.

As demonstrated by this study, the machining of dentin greatly affects the cutting efficiency of nickel-titanium rotary files. This is in agreement with previous studies of nickel-titanium hand files [39]. However, this is not in agreement with Zuolo and Walton. Using a different methodology, they found that nickel-titanium rotary files did not show signs of wear after six minutes of use. Results of this study indicate that cutting efficiency deteriorates prior to visible signs of wear [44].
The use of bovine dentin as our substrate demonstrated that the hardness of this substrate is appropriate for the measurement of cutting efficiency of nickel-titanium rotary instruments. The hardness of bovine dentin has been reported to range vary between 61-89 KHN [59, 60]. The hardness of human dentin has been reported to vary between 20-83 KHN[57, 58]. Based on these findings, bovine dentin demonstrates less variation in hardness as well as being a harder substrate than human dentin. This makes bovine dentin an ideal substrate to test the wear of nickel-titanium rotary files. Our study is in agreement with Kazemi et al. who have shown that wear of nickel-titanium instruments can be demonstrated on dentin and that dentin will continuously wear the endodontic file creating successive change in the instrument during instrumentation [38]. Based on our findings, the use of bovine dentin is an appropriate substrate for the testing of wear for endodontic rotary instruments.

This study also demonstrates that the use of a canal lubricant is of great importance as the file’s cutting efficiency declines. Irrigation is essential during machining efficiency experiments to prevent clogging of the instrument which will result in lower machining ability [40]. This study agrees with Yguel-Henry et al. who also found lubrication to increase the cutting efficiency of endodontic files [72]. This was evident for the Dry condition groups in runs one and two. During the second run, 6 of the 10 instrumented samples were in excess of five minutes. This indicates that the instrument is not as effective machining dentin therefore, the use of lubrication to remove dentin debris becomes more important for cutting efficiency. Using lubrication, all files in both the Glyde and Saline groups were able to instrument the canal in less than five minutes. The use of chelating agents has been reported to decalcify dentin to a depth of
20-30 um in five minutes [73]. Therefore, our use of Glyde as a lubricant has a minimal effect on the softening of the dentin substrate and as a result minimal affect on instrumentation time.

Interpreting the results of this study, variations in dentin and instrument quality must be considered. Variations have been shown for bovine dentin depending on the location and depth of the examined area [56]. Variations have also been shown in endodontic instruments [74]. However, given these parameter variations, the results of this study show a relatively small standard deviation of the test groups. Therefore, this model represents a standardized technique for the evaluation of nickel-titanium rotary instruments.

The rotational speed chosen for this study was 300 rpm. This is the recommended speed by the manufacturer of ProFile® 0.04 mm/mm nickel-titanium rotary files. Using extracted human teeth, Gabel et al. found that file separation/distortion is four times more likely to occur at 333.33 rpm than at 166.66 rpm [75]. Dietz et al., using a bovine bone model, also found that a speed of 150 rpm is less likely to cause instrument separation compared to higher speeds [76]. However, Yared and Sleiman found that speeds of 350 rpm can be used safely for the instrumentation of the root canals of extracted human teeth [77]. This study did not examine possible differences by using different rotational speeds, but during the instrumentation of seventy-five standardized dentin canals at a speed of 300 rpm, only one instrument separated during instrumentation.

The objectives of this study were to design a standardized dentin model for the evaluation of certain aspects of the cutting and machining qualities of nickel-titanium rotary instruments. The results demonstrate that an objective method is possible for the
evaluation of nickel-titanium rotary file wear. The use of such a model will further the understanding of the mechanical properties of nickel-titanium rotary files.

The standardized testing of nickel-titanium rotary instruments using a dentin substrate is not prevalent in endodontics. This study supports the recommendation of Stenman and Spångberg [40] that procedures should be agreed upon for the evaluation of machining and cutting efficiency of endodontic instruments and that a framework for such performance requirements be developed.
The mounting of each tooth was facilitated by the use of a surveyor. A surveyor stylus was placed inside the root canal to hold the tooth in a perpendicular plane to the surveyor platform. Plastic molds measuring 25 mm x 25 mm x 25 mm were filled with freshly mixed tooth acrylic and the tooth was lowered until it was flush to the CEJ. After setting, the acrylic block and the mold were marked on the same side with a permanent marker for orientation purposes to insure the same position during sample manipulation.
Figure 2

The sample was placed in a Buehler® Isomet™ low speed saw and positioned to remove 1mm from the coronal aspect of the sample to yield a flat surface perpendicular to the long axis of the tooth for the drilling of the canals.
Figure 3

A carbide drill of 0.35 mm diameter and 5 mm length was used to create simulated canals in the dentin samples.
Figure 4

An 8-inch drill press with a 1/3 horsepower motor used for all canal preparation.
Figure 5

Four canals were drilled in the coronal surface of the first segment of the sample.
Figure 6

The initial four canals that were drilled in the coronal surface of the first segment were cut leaving pilot holes in the second segment. The black markings were used to insure the proper positioning of the sample in the acrylic mold during cutting.
Figure 7

The segments were assembled by placing straight stainless steel wire of 0.33 mm diameter through the canals to properly align the segments.
Figure 8

Cyanoacrylate was used to secure the three segments. During drying the segments were held with binder clips.
Figure 9

The glued segments were secured with 0/80 x ½” machine screws at two opposite corners of the acrylic mold. This prevented the segments from separating when placed in the vise during the instrumentation of the canal.
Figure 10

The testing apparatus consisted of a platform guided by fixed wheels on a track of 16 inches in height. The platform was equipped with a counterbalance that would allow the control of the load applied to the platform.
To simulate a clinical “pecking” movement, the testing apparatus was equipped with an variable position electric motor with an eccentric movement. This provided the adjustable axial movement of the hand piece.
To calculate the time of instrumentation, the start/stop circuit of an Accusplit® stopwatch with readings of 1/100th second, was modified so that a Root ZX® file clip attached to the rotating file, would stop the timer when the file contacted the metal contact bar below the sample.
Figure 13

The mounted hand piece with the Root ZX® clip attached to the nickel-titanium rotary file prior to instrumentation of the canal.
Figure 14

During instrumentation of the Dry group, compressed air was used to remove dentin debris from the file.
Figure 15

During instrumentation of the saline group, following the air application, a 10 ml Luer-Lok™ syringe with a Monoject® 27 gauge needle was used to apply saline.
During instrumentation of the Glyde group, the paste was applied to the tip of a cotton swab to wipe the file and remove dentin debris while applying the lubricant.

Figure 16
Table 1

Instrumentation time for Dry, Glyde, and Saline groups.
Effects of irrigation on instrumentation time

<table>
<thead>
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<th>Glyde (min)</th>
<th>Saline (min)</th>
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<td>15</td>
<td>5.65</td>
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Mean 1.75 1.52 1.80
SD 1.28 0.69 0.88
Table 2

First and second run instrumentation time for the Dry group.
Instrumentation wear

Dry

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Table 3

First and second run instrumentation time for the Glyde group.
## Instrumentation wear

### Glyde

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| Mean | 1.991         | 2.811         |
| SD   | 0.923646      | 1.304509      |
Table 4

First and second run instrumentation time for the Saline group.
Instrumentation wear

Saline

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