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Comparative Analysis of WaveOne and LightSpeed LSX for the Residual Dentin Thickness of the Bifurcated Maxillary First Premolar Buccal Root Utilizing Limited Field Cone Beam Computed Tomography

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A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Dentistry at Virginia Commonwealth University.

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Abstract

COMPARATIVE ANALYSIS OF WAVEONE^{TM} AND LIGHTSPEED LSX^{TM} FOR THE RESIDUAL DENTIN THICKNESS OF THE BIFURCATED MAXILLARY FIRST PREMOLAR BUCCAL ROOT UTILIZING LIMITED FIELD CONE BEAM COMPUTED TOMOGRAPHY

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The purpose of this study was to compare the thickness of dentin removed from the buccal root of bifurcated maxillary first premolars (BMFP) in the area of furcation groove after instrumentation with WaveOne and LightSpeed LSX files utilizing limited field cone beam computerized tomography. All data was analyzed using repeated-measured mixed-model ANOVA and differences were described using Tukey's multiple comparison procedure.

The thickness of dentin removed with LightSpeed LSX files (0.1 mm) was significantly less than the thickness of dentin removed with WaveOne files (0.2 mm). To conclude, LSX files remove a more predictable and consistent thickness of dentin from the buccal root of BMFP, irrespective of the pre-instrumentation thickness of dentin and the file size when compared to WO files that remove a more variable thickness of dentin.

Introduction

The primary goal of non-surgical root canal treatment is to clean the entire root canal system of the organic pulpal remnants and inorganic debris. The canals are shaped in order to adequately disinfect them and subsequently obturate them to obtain a fluid tight seal with a biocompatible material. While performing endodontic therapy, the clinician should preserve the tooth and root structure thereby avoiding iatrogenic damage. Every attempt should be made to conserve radicular dentin, especially in areas of risk such as developmental depressions, concavities and grooves.

Instrumentation that effectively cleans and shapes canals results in removal of dentin from the canal walls, often weakening the root structure. Restoration of endodontically treated teeth with posts can also compromise the structural integrity of roots leading to their fracture. Post placement and root canal treatment are the major etiological factors for vertical root fracture (VRF) of endodontically treated teeth (1). Cohen, in his demographic analysis indicated that VRFs are statistically more prevalent in mandibular molars and maxillary premolars (2). Kishen, outlined the mechanisms and risk factors for fracture predilection in endodontically treated teeth. He stated that the loss of dentin tissue compromises the mechanical integrity of the remaining tooth structure. The intensity of stress concentration and tensile stresses depends upon, among other factors, the amount of available tooth structure (3). The prevalence of VRFs in endodontically treated teeth has been studied by different authors and found to be 10.9% (4),

12.9% (5) and 30.8% (6). Additionally, 56% of VRFs have been reported to involve maxillary premolars (7).

Traditional endodontic research has focused more on the internal anatomy of teeth rather than their external anatomy. During the biomechanical and post space preparation of root canals, it is important to be aware of the amount of tooth structure being removed, and also the external morphology of the tooth. External anatomic features like developmental depressions, fissures, and grooves on the crown-root surfaces have been implicated in the etiology of periodontal disease. These are more pronounced in certain teeth, which is a concern for the treating clinician.

The bifurcated maxillary first premolar (BMFP) often presents with unique anatomical features that require consideration when endodontically instrumenting or preparing a prosthetic post space. The prevalence of BMFPs has been found to be 61% of maxillary first premolars (8). According to Pucci and Reig, 54.6% of maxillary first premolars have two roots; and, according to Black, 60% of maxillary first premolars have two roots. BMFP has been studied for the presence of a developmental groove on the lingual surface of the buccal root (Fig. 1). The groove was previously reported as a "developmental depression" (9), a "buccal furcation groove" (10), or a "furcal concavity" (11). Though, the prevalence of this external anatomic feature is very high, ranging from 62% to 100% (9-11), few morphometric studies have been conducted to describe its characteristics.

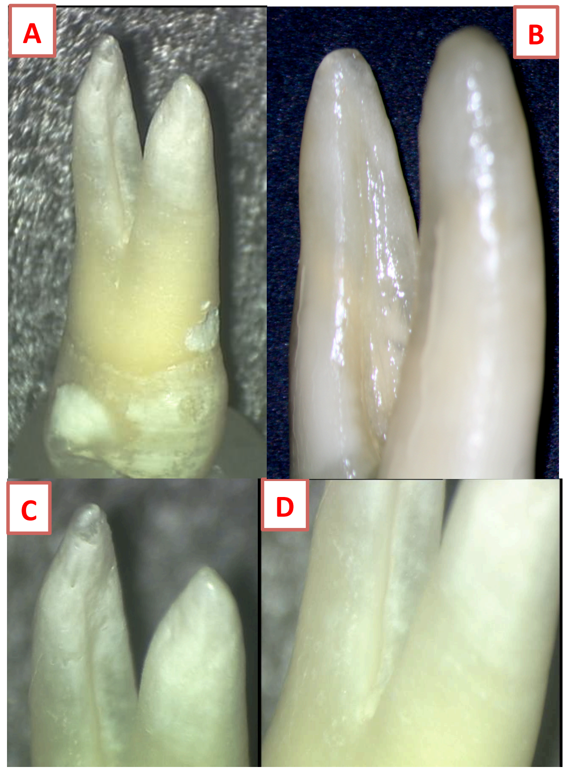


Figure 1: BMFP with developmental groove on the lingual surface of buccal root

Tamse et al were the first to conduct a morphometric study on the buccal furcation groove in a sample of freshly extracted BMFPs (12). They described the groove as starting just apical to the bifurcation, reaching a mean maximal depth of 0.4 mm at a mean distance of 1.18 mm from the bifurcation, becoming gradually shallower, travelling to a mean distance of 5.38 mm and disappearing towards the apex. The mean thickness of palatal dentin at the level of deepest invagination of the groove was found to be 0.81 mm. They noted that in the vertical plane, a negative co-relation exists between the distance of the bifurcation from the top of the buccal cusp and the distance of the deepest invagination from the bifurcation. This implies that,

as the bifurcation is located more coronally, the deepest invagination is more remote from the bifurcation and vice-versa. Tamse et al concluded that the furcation groove of the buccal root of BMFP necessitates the reappraisal of the quantity of dentin removed during endodontic preparation or the application of posts in the buccal root for tooth restoration.

Lammertyn et al assessed 141 BMFPs to accomplish an anatomic study of furcation grooves and dentin width in buccal roots (13). They found that 83% of studied teeth had furcal grooves in the buccal root; the mean depth of this groove was 0.05mm in the apical third, 0.34mm in the middle third, and 0.36mm in the coronal third. Different authors have found the mean thickness of palatal dentin to be 1.18mm (13), 1.31mm (14) and 0.99mm (15).

Historically, there has been an emphasis on preparing evenly tapered root canals. Schilder had suggested that root canal preparation should develop a continuously tapering funnel from the root apex to the coronal access cavity (16). This is essential to effectively clean the root canal system and to permit the compaction of gutta percha. Coffae showed that serial preparations were significantly more effective than non-serial preparations in removal of tissue at all three levels studied (1, 3 and 5 mm) in the root canals (17). Christie recommended tapered preparation over standardized preparation of curved root canals (18). The tapered preparation leaves a smaller apex, has more taper in the apical 5 mm and is opened larger in the coronal half of the canal. Buchanan introduced the use of greater taper files with minimal apical enlargement to limit extrusion of obturating materials. Wu and Wesselink compared the step-back, crown-down pressureless, and balanced-force techniques in their ability to clean the apical portion of curved root canals (19). They concluded that the balanced-force technique gave the cleanest apical canal because with this technique the largest apical file could be used. Albrecht and Baumgartner evaluated the effect of preparation taper on the ability to introduce irrigant and

remove debris from root canals (20). Their results showed that debris is more effectively removed using 0.04, 0.06, and 0.08 ProFile GT instruments when the apical preparation size is larger (size #40) compared with size #20 apical preparations.

The structural integrity of the root canal system is impacted by the size and taper of the instruments used to shape the canal. Remaining residual dentin thickness (RDT) is considered a critical factor following canal preparation for both prosthetic restoration and long-term prognosis of a tooth. A compromise in the remaining RDT may predispose the tooth to lateral or strip perforations (1-3) or root fracture. Caputo and Standlee have suggested that at least 1.0 mm of circumferential sound tooth structure is required to resist possible root fracture when a prosthetic post is required to restore a tooth (21).

Lim and Stock attempted to establish a minimal RDT required for sustainment of root integrity during lateral condensation (22). They speculatively set 0.3 mm as the minimal remaining RDT at which condensation forces may exceed the resistance of the dentin and thus lead to perforation or fracture. Their study did not account for the cementum layer present on roots and assumed the proposed 0.3 mm minimum was dentin alone.

McCann et al suggested that RDT is composed histologically of both the remaining dentin and intact cementum layers and should be referred to as dentin-cementum wall (DCW) thickness (23). They speculatively set 0.5 mm as the minimum DCW thickness required to prevent strip perforation or weakening of the mesial root in mandibular first molars following instrumentation.

Different instrumentation techniques have been reported to affect the amount of radicular dentin removed in the perforation prone areas of the root. Lim and Stock found that anticurvature filing preserved a greater thickness of the furcal wall than the stepback method and

reduced the risk of perforation (22). McCann compared the degree of encroachment upon the furcation area in mesial roots of mandibular molars during hand or ultrasonic instrumentation and found that both techniques came dangerously close to creating stripping and perforations in a high percentage of cases (23).

Recently, the WaveOne NiTi file system has been introduced to the marketplace. In this system a single NiTi (M-Wire technology) file is used in a reciprocating handpiece to completely prepare the canal to an adequate size and taper, even in narrow and curved canals (24). The specially designed NiTi files work in a reverse "balanced force" action using a pre-programmed motor to move the files in a back and forth "reciprocal motion". The motor is programmed such that the counterclockwise movement is greater than the clockwise movement; three reciprocating cycles complete one reverse rotation. Berutti et al found that the new WaveOne NiTi primary reciprocating file, if used after a previous glide path has been established, produced less modification in canal curvature compared with the WaveOne alone (25). Berutti et al in their subsequent study to compare the canal curvature and axis modification after instrumentation with WaveOne Primary file and Protaper found that canal modifications are reduced when the new WaveOne single-file system is used (26). Burklein et al compared the shaping ability and cleaning effectiveness of two reciprocating single-file systems (WaveOne and Reciproc) with two rotary instruments (Mtwo and ProTaper) and found that all instruments maintained the original canal curvature, the use of Mtwo and Reciproc instruments resulted in better canal cleanliness in the apical part than the ProTaper and WaveOne instruments (27). Burklein and Schafer, in their study of mandibular incisors, found that the full-sequence rotary instrumentation using Mtwo and ProTaper was associated with less debris extrusion when compared with the use of Reciproc and WaveOne reciprocating single-file systems (28).

LightSpeed LSX rotary instruments are non-tapered nickel-titanium files that are flexible and remain centered along the original canal path. These have a highly flexible non-tapered shaft, a stamped, short and spade-shaped blade design, and are used at 2,500 rpm in a high-torque handpiece. Zuckerman et al in their study of mesial roots of mandibular molars found that root canal preparation with LightSpeed instruments to No. 50 in the apical third and Gates-Glidden reamers to No. 2 in the coronal third does not significantly decrease the RDT (29). Their findings also established that LightSpeed rotary instruments cut all surfaces evenly, thus preventing the phenomena of cutting one surface and leaving other surfaces more or less untouched. Thompson et al conducted two in-vitro studies to determine the shaping ability of LightSpeed instruments. In their first study of simulated canals, LightSpeed instruments prepared canals rapidly, with no fractures, canal blockages, and with minimal change in working length (30). The subsequent study showed that LightSpeed instruments maintained the original shape of the canal and the degree of absolute transportation was small with no significant differences between the canal shapes in the region apical to the curve (31). They concluded, "Lightspeed rotary instruments prepared canals well and would appear to be a valuable addition to the endodontic armamentarium". Portenier et al measured in-vitro the displacement of natural canal centers in human teeth before and after shaping by the step-back or LightSpeed techniques (32). LightSpeed instruments caused significantly less displacement of the canal centers and the mean cross-sectional area of the canal after preparation in the LightSpeed group was significantly less than that recorded in the step-back group. Clinically, this implies less apical transportation and less dentin destruction with the LightSpeed technique than with the step-back technique. Tharuni et al showed that K-files caused more widening at the apical end with higher incidence of transportation, zipping and elbow formation when compared with LightSpeed

instruments that stayed centered in the canal (33). Weller et al found that there were statistically significant differences in the RDT in the apical 4 mm of mandibular incisors and mesiobuccal canals of mandibular molars following cleaning and shaping with SS Flexofiles, LightSpeed, Profile and K3 instrumentation techniques (34). They concluded that instrumentation to a larger master apical rotary file utilizing LightSpeed did not reduce RDT to any statistically significant degree.

Bramante et al (35) described a method for comparing root canal anatomy before and after instrumentation utilizing a muffle. Teeth were embedded in a colorless acrylic resin block and transverse grooves were placed at levels in which the tooth would be sectioned for examination. The resin block was covered in a plaster muffle and sectioning of the aforementioned grooves was accomplished with a carborundum disc. The muffle functioned as a matrix to reposition each section in order to facilitate instrumentation. This methodology was the standard in which all early comparative instrumentation studies were performed.

Periapical radiographs are considered standard of care in endodontic treatment (36). Two-dimensional (2D) radiographs are of significant value to the clinician but are of limited use when determining location of various anatomical features. Three-dimensional (3D) radiographic images could potentially be of benefit when treatment planning or providing endodontic treatment. 3D image representation of changes in DCW thickness before and after instrumentation has been previously studied (37). The use of Cone Beam Computed Tomography (CBCT) continues to gain momentum in both non-surgical and surgical endodontic treatment planning (37-39). The CBCT provides a noninvasive evaluation method for both the external and internal morphology of a tooth (37-39). A characteristic of CBCT is its ability to measure both initial and post-instrumentation RDTs. This unique feature is important because it

provides a reliable control (initial RDT) against which each successively instrumented canal can be compared and analyzed.

Subsequent scans can be produced following canal preparation providing an excellent way to examine the root canal in a nondestructive manner (39). The use of the CBCT appears superior to 2D radiographs because it affords a virtual *in situ* image. Likewise, physical cross-sectioning of the root is avoided which can invariably result in a loss of 0.4 mm or greater in each horizontal cut (21, 35). Subsequently, the loss of tooth structure may affect the accuracy of post-instrumentation data. Kobayashi et al evaluated the accuracy of measurement of distance on the images produced by limited CBCT (40). Their data indicated that limited CBCT can be used to measure distance between points more accurately than Spiral Computerized Tomography. For the purpose of this study, a CS 9300 limited field CBCT machine (Carestream Health, Inc., Rochester, NY) was utilized at Virginia Commonwealth University School of Dentistry.

To date, no study has compared the performance of different rotary systems in terms of removal of dentin from the buccal root of BMFPs. Zigo et al studied the DCW thickness along the furcation groove in BMFPs after preparation with three successively larger, 0.04 tapered, nickel titanium rotary files using CBCT (41). They concluded that instrumentation of the mid-groove in BMFPs reduces the DCW thickness to levels that may be insufficient to ensure tooth integrity.

The purpose of this study was to compare the thickness of dentin removed from the buccal root of BMFPs in the area of furcation groove after instrumentation with WaveOne and LightSpeed LSX files utilizing limited field CBCT.

Materials and Methods

Ninety extracted human BMFPs were collected from various dental clinics and stored in 10% neutral buffered formalin. All teeth collected would have been disposed of accordingly, but were kept for the purpose of this study. The teeth were cleaned of any calculus or periodontal tissue remnants by scaling the root surface and then examined for the presence of the buccal furcation groove utilizing an operating microscope (Carl Zeiss, Inc., North America). Seventy-seven teeth exhibiting the furcation groove were selected. Later, two teeth had to be excluded because of the presence of more than one canal in the buccal root and three teeth had to be excluded due to lack of patency in the buccal canal. Finally, seventy-two teeth with furcation grooves were selected for the purpose of this study.

Each tooth was endodontically accessed with a #4 round bur (Henry Schein, Melville, NY) to ensure an ideal straightline access. The principle buccal and lingual canal orifices were identified with an operating microscope and an endodontic explorer. The buccal canal was explored for patency using a size 8 K-file (Dentsply Maillefer; Ballaigues, Switzerland).

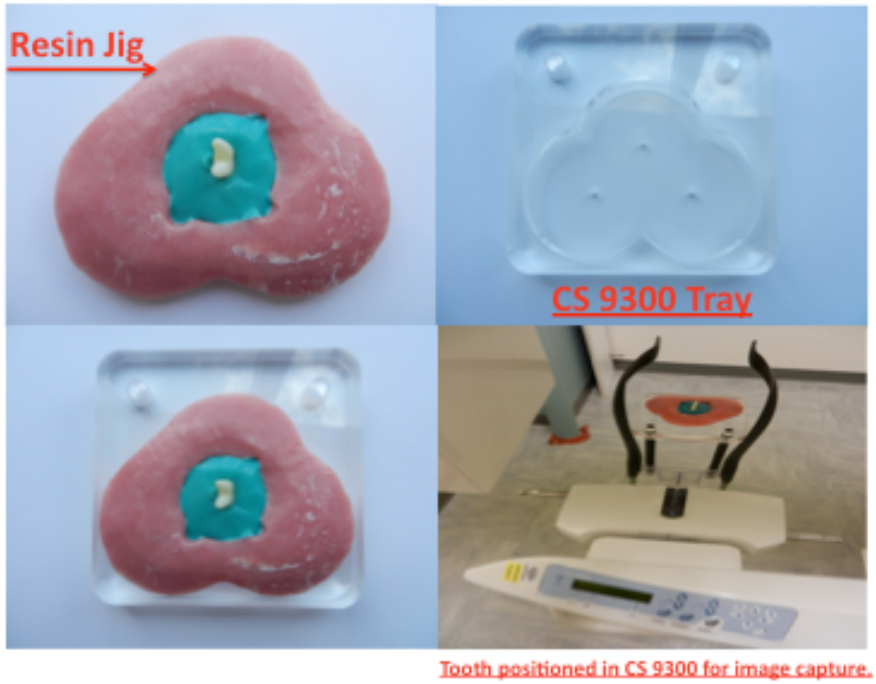


Figure 2: Resin Mounting Jig

Each tooth was mounted using polyvinyl siloxane impression material (Genie:Sultan,Englewood,NJ) on a custom made polymethylmethacrylate resin mounting jig with the access opening facing down. The jig was custom made to fit the tray provided with the CS 9300 limited field cone beam computed tomography (CBCT) machine (Carestream Health, Inc., Rochester, NY) (Fig. 2). This method of mounting allowed for precise repositioning with each subsequent CBCT scan. The field of view was set at 5 cm in diameter and 5 cm in height. The scan was set at 60-90 kV, 2-15 mA and 140 kHz, with a voxel size of 90 micrometers. The slice thickness was 90 micrometers, which is the smallest measurable width possible on this machine. A pre-instrumentation scan was obtained for each specimen. A desktop computer (Dell Inc., Round Rock, and TX USA) equipped with Carestream software and supporting hardware was used to make the measurements.

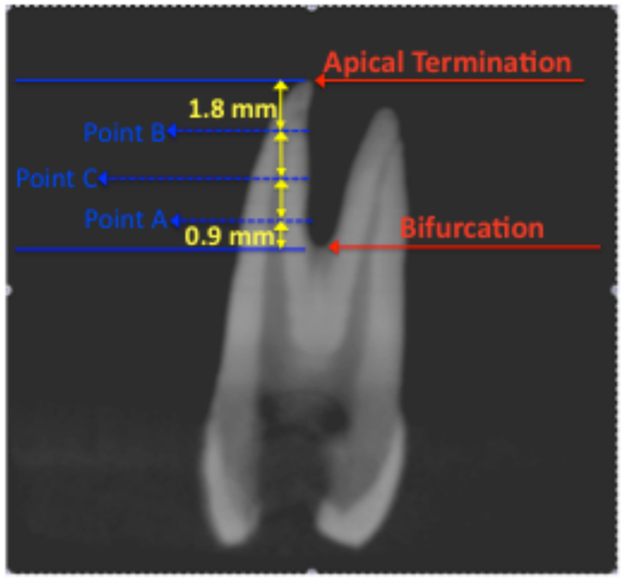


Figure 3: Specified locations for measurements along the furcation groove

RDT was measured within the axial plane at four specified locations (slice levels) along the furcation groove for each respective tooth. Figure 3 illustrates an example of each point or slice level measured along the furcation groove in a sagittal plane. The level of bifurcation of root and the apical termination point of the buccal root were recorded and used as reference points for the calculation of three out of the four specified locations. The bifurcation and apex were chosen as points of reference as these were expected to remain constant, and unaltered by the instrumentation of the canals. The first slice (Point A) was measured at 0.9 mm apical to the level of bifurcation. The second slice (Point B) was measured at 1.8 mm coronal to the point of apical termination of the root. These levels were chosen keeping in mind the aim of making the

measurements in the portion of the buccal root that exhibits the furcation groove. The third slice (Point C) was measured at the median slice number between the first and second slice numbers, Point A and Point B respectively. The fourth slice (Point D) was measured at the level of deepest invagination of the furcation groove into the canal wall, as subjectively identified by the author (MSS).

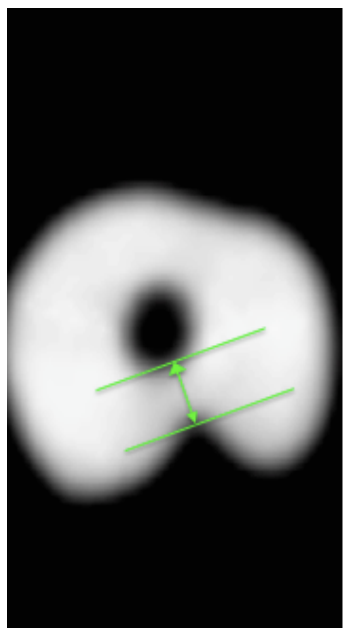


Figure 4: Method of RDT measurement in the axial view

RDT was measured between the deepest aspect of the furcation groove (i.e. concave aspect of the "C" in cross section) and the corresponding outer lingual wall of the canal. Figure 4 further depicts the method in which measurement of the RDT was completed. In Figure 4, two

horizontal lines are drawn parallel to each other and separated by a perpendicular line. The first horizontal line is drawn on tangent with the deepest invagination point of the furcation groove. The second horizontal line is drawn on a tangent with the innermost lingual portion of the canal wall. The perpendicular line connects both horizontal lines and represents the RDT present. All measurements were recorded in the axial plane in order to provide a repeatable horizontal measurement at the specified slice level. This measurement technique is consistent with other morphometric studies in which RDT width measures were obtained (23).

The teeth were then randomly divided into two groups, 36 teeth in each group. One group was instrumented with LightSpeed LSX (LSX) instruments (Sybron Dental Specialties Inc., Orange CA) and the other with WaveOne (WO) instruments (Dentsply Tulsa Dental Specialties Inc., Tulsa OK) following respective manufacturer's instructions. The working length (WL) was measured from the buccal cusp tip as the reference point. A size 8 K-file was introduced into the buccal canal and WL was recorded at the reference point when the file was visible exiting the apical foramen under the operating microscope. The final WL was calculated by subtracting 0.5 mm from the above recorded value. Canal irrigation was achieved with 5.25% sodium hypochlorite during instrumentation and delivered into the canal by a 10 cc syringe with a 30-gauge needle (Monoject; Sherwood Medical, St. Louis, MO). Straightline access into the buccal canal was achieved by using Gates Glidden #2 and #3 drills (Henry Schein, Melville, NY) into the most coronal 1.0 mm of the canal to remove any cervical dentin constriction. All the specimens were instrumented by a single experienced operator (MSS).

Lightspeed LSX instrumentation was accomplished according to the following manufacturer's guidelines (42). First, ensure canal patency to WL with a #15 K-file. Then begin with LSX #20, if #20 does not go easily to WL, further enlarge canal with #20 K-file. Continue

with sequentially larger sizes until the apical part of the canal is prepared to the correct Final Apical Size (FAS). This is the size that requires a firm push in the final apical 4 mm to advance it to WL. The FAS defines the Working Width (WW). It is the instrument size that is slightly larger than the original apical canal diameter. To complete apical shaping, instrument 4 mm short of WL with LSX that is one size larger than the FAS. Instrument the mid-root with sequentially larger instruments. Advance to resistance, pause, then push 2 to 3 mm apically. Repeat this step until reaching a size that will not easily advance past the coronal third of the canal. Mid-root instrumentation usually requires three instruments. Using the FAS rotating in the handpiece, recapitulate to WL. Then stop the handpiece rotation and confirm the existence of an apical stop by attempting to push the FAS past the WL. The FAS should not advance past the WL. The FAS was recorded for each tooth.

WaveOne instrumentation was accomplished according to the following manufacturer's guidelines (43). The first step is WaveOne file selection. At present, there are three files available in the WO single-file reciprocating system. The WO Small file has a tip size of ISO 21 with a continuous taper of 6%. The WO Primary file has a tip size of ISO 25 with an apical taper of 8% that reduces towards the coronal end. The WO Large file has a tip size of ISO 40 with an apical taper of 8% that reduces towards the coronal end. If a #10 K-file is very resistant to movement, use WaveOne Small file, if a #10 K-file moves to WL easily, is loose or very loose, use WaveOne Primary file, if a #20 K-file or larger goes to WL, use WaveOne Large file. Take hand file into canal and watch-wind to WL or resistance (approximately two-thirds of canal length). Use appropriate WO file to approximately two-thirds of canal length, irrigate copiously, take hand file to length and then take WO file to length. The foramen diameter is confirmed with hand file of the same size as WO file. If the hand file is snug, preparation is complete. If

the hand file is loose that means foramen diameter is larger than WO file, consider the next larger WO file. Use WO files with a progressive up and down movement no more than three to four times, only little force is required. The file should be cleaned and canal irrigated regularly. The WO file used for final apical preparation for each tooth was recorded in terms of it's tip size i.e., if WO Small file was used, tip size of 21 was recorded; 25 for WO Primary and 40 for WO Large file was recorded.

After completing the instrumentation, teeth were repositioned in the resin jig for the post-instrumentation scan. By using the manufacturer provided tray and the custom made resin jig for the tray, it was ensured that the teeth were repositioned in the same three-dimensional orientation for the subsequent images. All the measurements at different slice levels were recorded for the post-instrumentation images. While reading the images, the operator (MSS) was blinded to the information of the type of instrument (LSX or WO) used in that particular tooth. This helped reduce the operator bias.

It was considered necessary to first describe the pre-instrumentation thickness at each of the locations. This was done by using a repeated-measured mixed-model ANOVA which takes into account the correlation of the thicknesses across the four locations. Differences were described using Tukey's multiple comparison procedure. For the differences between the pre-instrumentation thicknesses, the following effects were included in the model: instrument (WaveOne or LightSpeed LSX), location (A, B, C, D), and the instrument-location interaction. The same effects were included in the model to compare the post-instrumentation thicknesses plus the pre-test thickness was included as a covariate. All analyses were performed using SAS software (SAS version (9.3, JMP-pro version 10.0, SAS Institute, Inc., Cary NC).

Results

Seventy-two teeth were randomly assigned to one of two instrumentations (Table 1). The two instrumentation groups were not significantly different on instrument size (t-test = 1.95, P = 0.0553). The average LSX size was 34.03 (SD = 4.11) and the average WO size was 31.25 (SD = 7.50).

Table 1: Instrument size distribution

Instrument	**Size**	**N**
LSX	30	15
	35	14
	40	6
	45	1
	Total	36
WO	25	21
	40	15
	Total	36

Pre-instrumentation Findings

The n = 36 teeth in each instrumentation group had a measured thickness at each of the four locations, as shown in Table 2. A repeated-measures ANOVA was used to compare the mean thickness by location and instrument group. The results indicated no difference due to instrument ($P > .7$) but a difference between locations ($P < .0001$). The differences between locations was consistent across the two instruments ($P > .9$). Significant differences between the locations are described in Table 3. Tukey's HSD indicated that the midpoint (Point C) was thinnest and that 0.9 mm apical to the bifurcation (Point A) was thickest.

Table 2: Pre-instrumentation Thickness by Location and Instrument

Location	Instrument	Mean	SD	Range	
Point A	LightSpeed	1.19	0.22	0.81	1.60
	WaveOne	1.16	0.23	0.61	1.60
Point B	LightSpeed	1.05	0.24	0.51	1.50
	WaveOne	1.02	0.28	0.36	1.80
Point C	LightSpeed	0.89	0.19	0.39	1.30
	WaveOne	0.89	0.26	0.23	1.40
Point D	LightSpeed	1.09	0.23	0.60	1.60
	WaveOne	1.07	0.28	0.22	1.60

Abbreviations: Location Point A= 0.9mm apical to the bifurcation, Point B = 1.8mm coronal to the apex, Point C = midway between A and B, Point D = deepest invagination, SD = standard deviation.

Table 3: Pre-instrumentation Thickness Differences by Location

Location	Mean	SE	95% CI		*
Point A	1.177	0.029	1.120	1.234	A
Point B	1.033	0.029	0.977	1.090	B
Point C	0.889	0.029	0.832	0.946	C
Point D	1.083	0.029	1.026	1.140	B
All	1.046	0.026	0.994	1.097	

* Means not connected by the same letter are significantly different by Tukey's multiple comparison procedure.

In addition to the differences between the pre-instrumentation mean thicknesses, the correlation between the four locations is also evident (Table 4).

Table 4: Correlation between the Thickness Measurements Across the Locations

Location	Point B	Point C	Point D
Point A	0.25	0.31	0.30
Point B		0.25	0.60
Point C			0.12

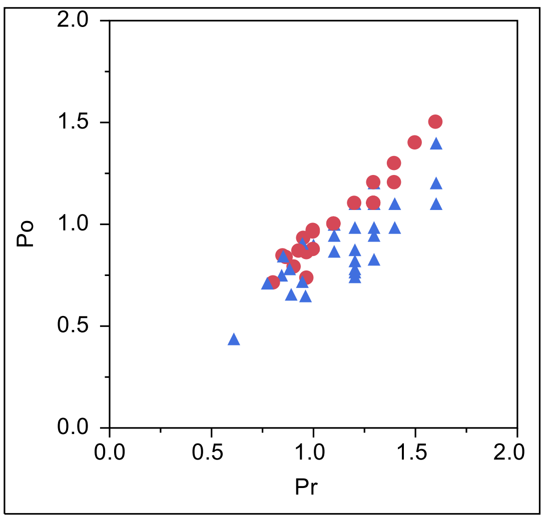
Abbreviations: Location Point A= 0.9mm apical to the bifurcation, Point B = 1.8mm coronal to the apex, Point C = midway between A and B, Point D = deepest invagination, SD = standard deviation.

Post-instrumentation Findings

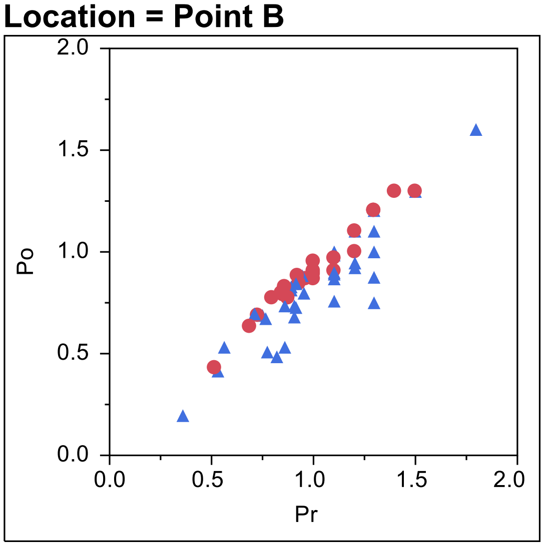
To test whether the post-instrumentation thickness is different depending upon the type of instrument used, a repeated-measures mixed-model ANCOVA was used. The pre-instrumentation covariate account for the relationship between the pre- and post-thickness

measures (Figure 5). The following effects were included in the model: the pretest thickness covariate, instrument (WaveOne or LightSpeed LSX), location (A, B, C, D), and the instrument*location interaction. The ANCOVA results indicated that the pre-instrumentation covariate was significantly related to the post-instrumentation thickness ($P < .0001$). Since the interaction was significant ($P = 0.0407$), it indicates that the differences between the instruments varied depending upon the location. Thus, results will be shown separately for each location as well as overall.

Location = Point A



Location = Point B



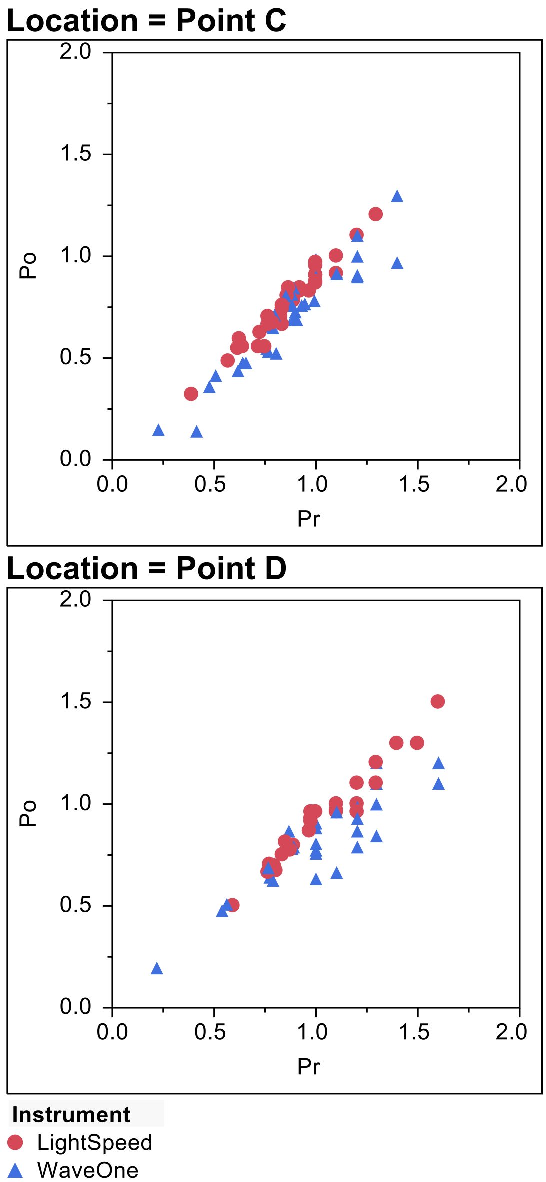


Figure 5: Relationships between Pre- and Post-Instrumentation Thickness

The average post-instrumentation thickness for each location and instrument is shown in Table 5 and Figure 6. Averaging across all locations, the LSX least squared mean thickness was 0.942 mm, as compared to the WO least squared mean thickness of 0.849 mm. The LSX was -0.093 mm thinner ($P < .0001$, 95% CI = -0.120 to -0.066). As is seen in Table 5 and Figure 6,

across all locations WO left significantly thinner dentin ($P = 0.0001$). The least squared mean estimated post-instrumentation thickness is given for the mean pre-instrumentation thicknesses shown in Table 3. Also evident in Figure 6 is a significant difference across the locations for LSX ($P < .0001$) and a significant difference across the locations for WO ($P < .0001$). Not only are the mean thicknesses different across locations for WO, the confidence intervals around the means are also larger. This indicates more variability in the thickness for WO.

Table 5: Post-Instrumentation Thickness by Location and Instrument

Location	Instrument	LS Mean	SE	95% CI		p-value
Average	LightSpeed	0.942	0.005	0.932	0.953	
	WaveOne	0.849	0.012	0.824	0.874	
	Difference	0.093	0.013	0.066	0.120	< .0001
Point A	LightSpeed	1.068	0.009	1.050	1.086	
	WaveOne	0.942	0.021	0.900	0.984	
	Difference	0.126	0.023	0.081	0.172	< .0001
Point B	LightSpeed	0.931	0.007	0.917	0.945	
	WaveOne	0.843	0.018	0.806	0.879	
	Difference	0.089	0.019	0.050	0.127	< .0001
Point C	LightSpeed	0.791	0.007	0.777	0.805	
	WaveOne	0.727	0.014	0.699	0.755	
	Difference	0.064	0.016	0.033	0.095	0.0001
Point D	LightSpeed	0.979	0.007	0.964	0.993	
	WaveOne	0.885	0.019	0.846	0.923	
	Difference	0.094	0.020	0.053	0.135	< .0001

Abbreviations: Location Point A= 0.9mm apical to the bifurcation, Point B = 1.8mm coronal to the apex, Point C = midway between A and B, Point D = deepest invagination, LS Mean = least squared mean estimate at the average pre-instrumentation thickness, SE = standard error, CI = confidence interval.

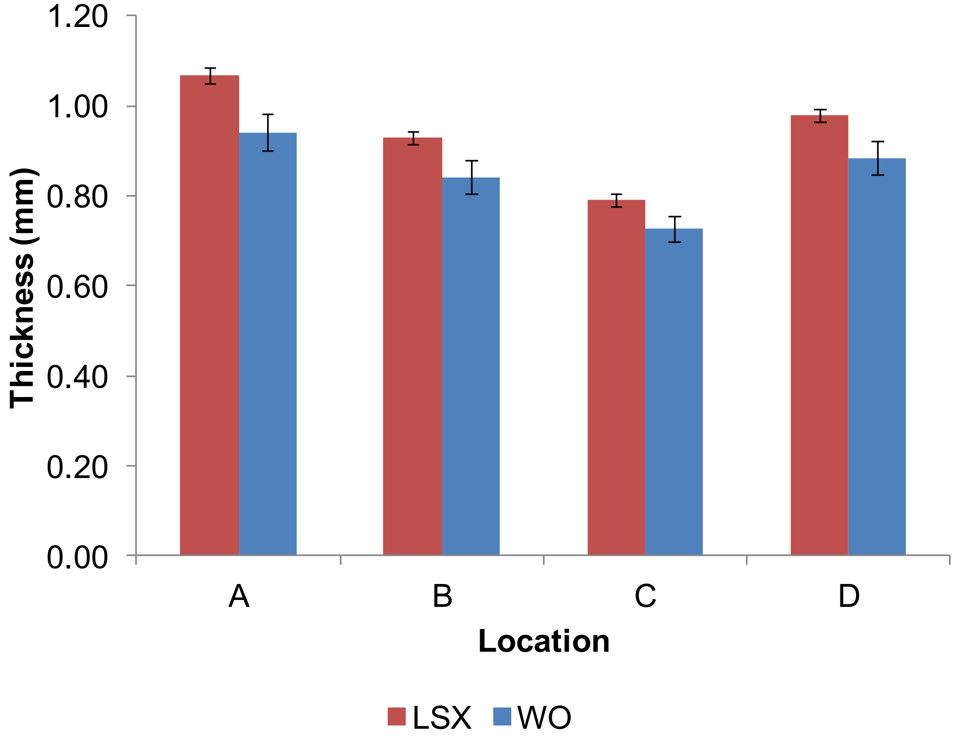


Figure 6: Post-Instrumentation Thickness by Location and Instrument

It is useful to consider the percentage of teeth whose post-instrumentation thickness of dentin was below certain critical values. Specifically, the cases whose post-instrumentation thickness was ≤ 0.5 mm and those whose thickness was ≤ 1 mm. The number and percentage of teeth with thickness ≤ 0.5 mm is shown in Table 6 and Figure 7. As may be seen, the LSX has fewer instances of thin dentin. For LSX, an average of 2.1% of teeth had thickness ≤ 0.5 mm and for WO, an average of 9% of teeth had thickness ≤ 0.5 mm.

Table 6: Percentage Thickness ≤ 0.5 mm

Location	Instrument	n	Percent	95% CI	
Point A	LightSpeed	0	0.0	0.0	9.6
	WaveOne	1	2.8	0.5	14.2
Point B	LightSpeed	1	2.8	0.5	14.2
	WaveOne	3	8.3	2.9	21.8
Point C	LightSpeed	2	5.6	1.5	18.1
	WaveOne	7	19.4	9.8	35.0
Point D	LightSpeed	0	0.0	0.0	9.6
	WaveOne	2	5.6	1.5	18.1

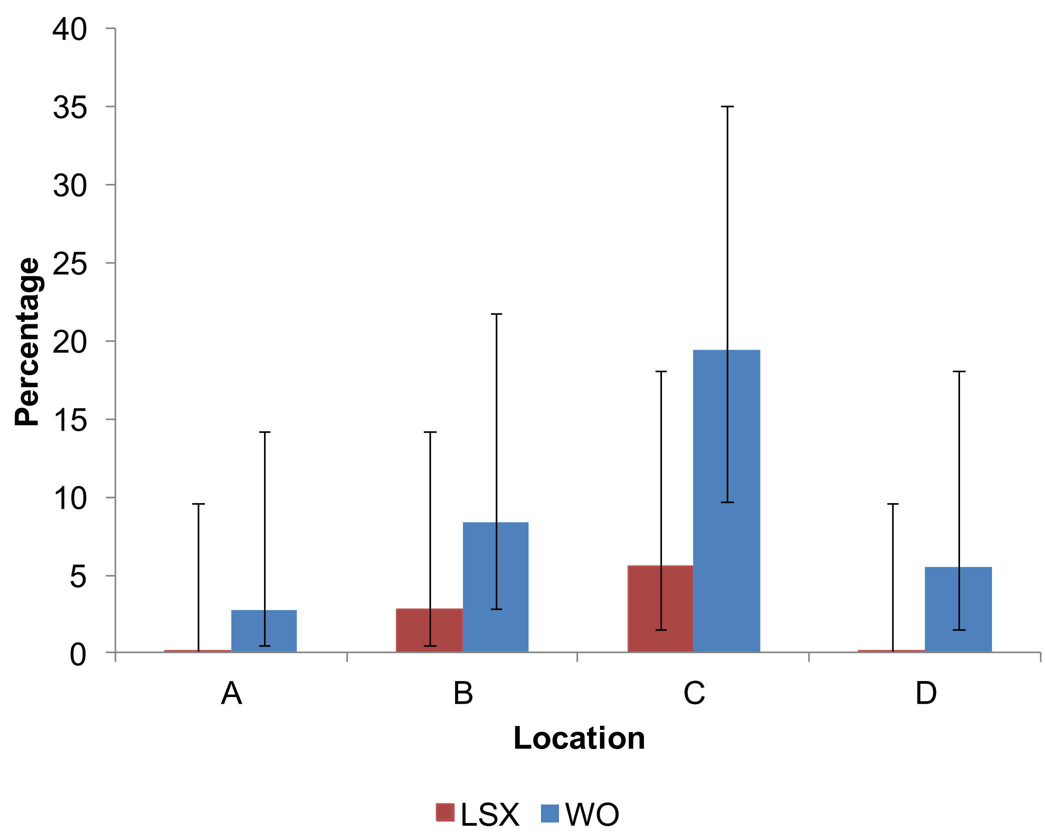


Figure 7: Percentage Thickness ≤ 0.5 mm

The number and percentage of teeth with thickness ≤ 1mm is shown in Table 7 and Figure 8. As may be seen, there are more instances of thinness and, in most cases, the LSX has fewer instances of thin dentin. For LSX, an average of 68.7% of teeth had thickness ≤ 1 mm and for WO, an average of 80.6% of teeth had thickness ≤ 1 mm.

Table 7: Percentage Thickness ≤ 1 mm

Location	Instrument	n	Percent	95% CI	
Point A	LightSpeed	16	44.4	29.5	60.4
	WaveOne	25	69.4	53.1	82.0
Point B	LightSpeed	26	72.2	56.0	84.2
	WaveOne	30	83.3	68.1	92.1
Point C	LightSpeed	34	94.4	81.9	98.5
	WaveOne	34	94.4	81.9	98.5
Point D	LightSpeed	23	63.9	47.6	77.5
	WaveOne	27	75.0	58.9	86.2

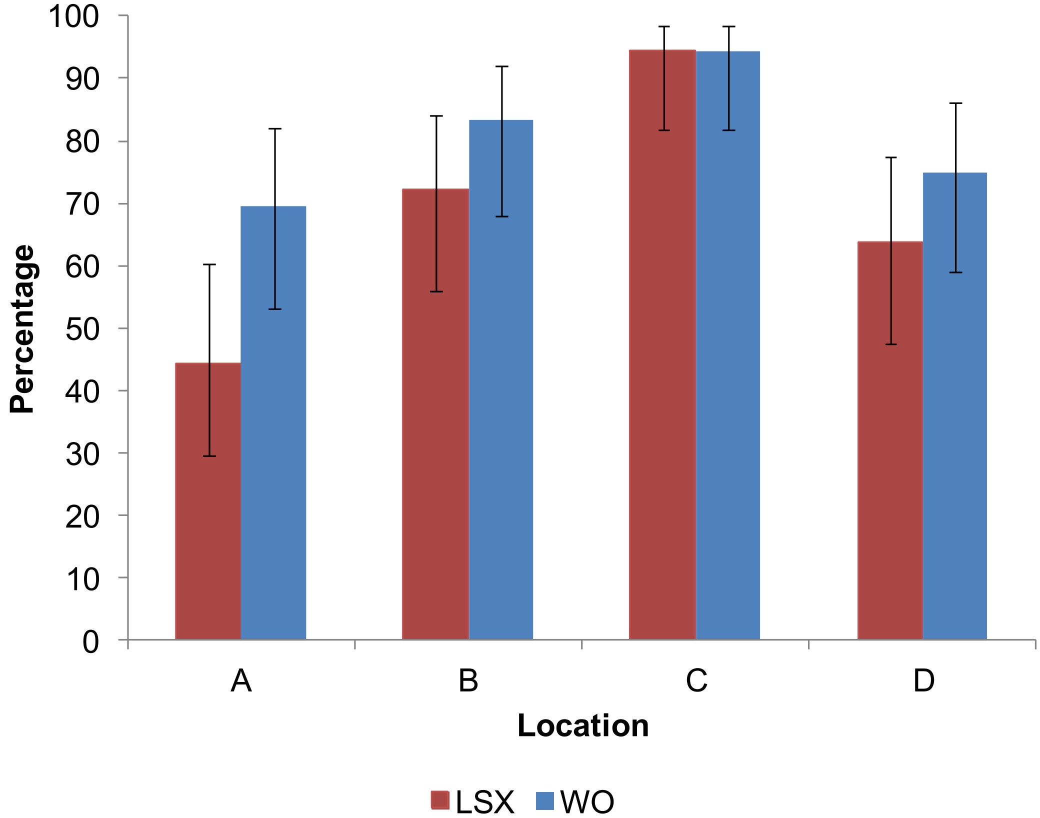


Figure 8: Percentage Thickness ≤ 1 mm

Thickness of Dentin Removed

This analysis used an identical repeated-measures mixed-model ANCOVA as in the analysis of the post-instrumentation thickness. The only difference in the analysis was using the pre-post difference as the outcome variable. The average difference between pre-instrumentation thickness and post-instrumentation thickness for each location and instrument is shown in Table 8 and Figure 9. Averaging across all locations, the LSX least squared mean removed was 0.104 mm, as compared to the WO least squared mean removal of 0.197 mm. The LSX removed -0.093 mm less ($P < .0001$, 95% CI = -0.120 to -0.066). As is seen in Table 8 and Figure 9,

across all locations LSX removed significantly less dentin (*P* = 0.0001). Also evident in the Figure 9 is that there is no significant difference across the locations for LSX (*P* > .75) but there is a significant difference across the locations for WO (*P* = 0.0039). Not only are the mean removal different across locations for WO, the confidence intervals around the means are also larger. This indicates more variability in the removal of dentin thickness for WO.

Table 8: Thickness of Dentin Removed by Location and Instrument

Location	Instrument	LS Mean	SE	95% CI		p-value
Average	LightSpeed	0.104	0.005	0.093	0.114	
	WaveOne	0.197	0.012	0.172	0.222	
	Difference	-0.093	0.013	-0.120	-0.066	<.0001
Point A	LightSpeed	0.109	0.009	0.091	0.127	
	WaveOne	0.235	0.021	0.193	0.277	
	Difference	-0.126	0.023	-0.172	-0.081	<.0001
Point B	LightSpeed	0.102	0.007	0.088	0.116	
	WaveOne	0.191	0.018	0.154	0.227	
	Difference	-0.089	0.019	-0.127	-0.050	<.0001
Point C	LightSpeed	0.098	0.007	0.084	0.113	
	WaveOne	0.162	0.014	0.134	0.190	
	Difference	-0.064	0.016	-0.095	-0.033	0.0001
Point D	LightSpeed	0.104	0.007	0.090	0.119	
	WaveOne	0.199	0.019	0.160	0.237	
	Difference	-0.094	0.020	-0.135	-0.053	<.0001

Abbreviations: Location Point A= 0.9mm apical to the bifurcation, Point B = 1.8mm coronal to the apex, Point C = midway between A and B, Point D = deepest invagination, LS Mean = least squared mean estimate at the average pre-instrumentation thickness, SE = standard error, CI = confidence interval.

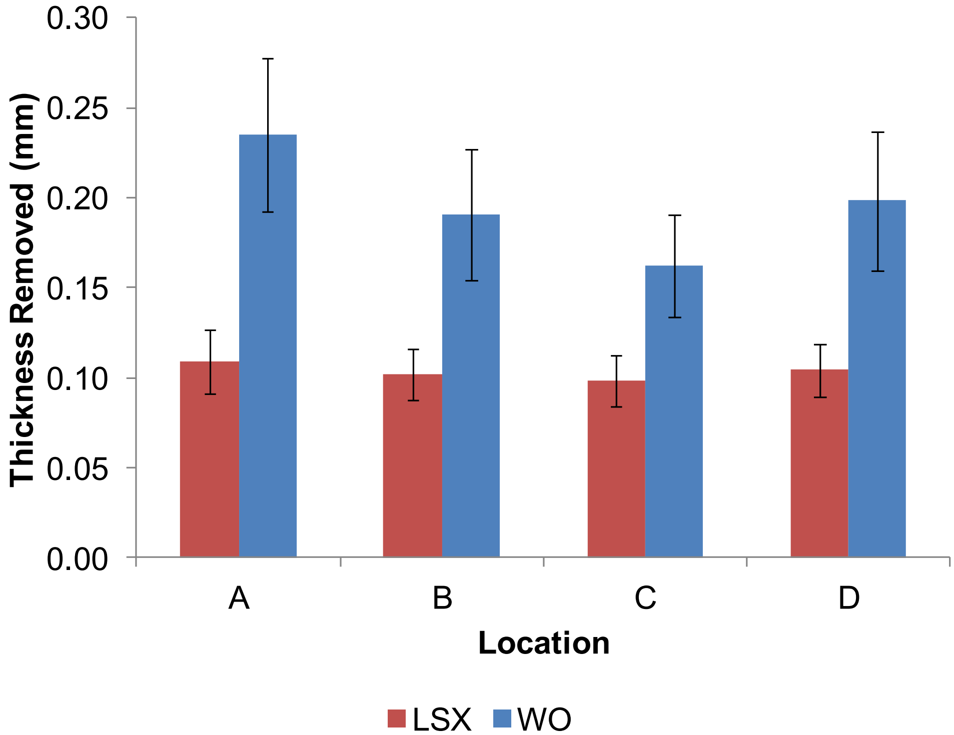
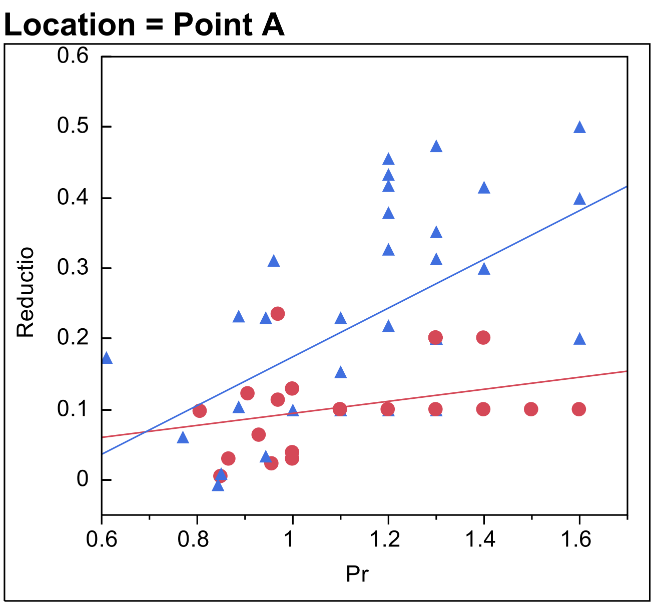


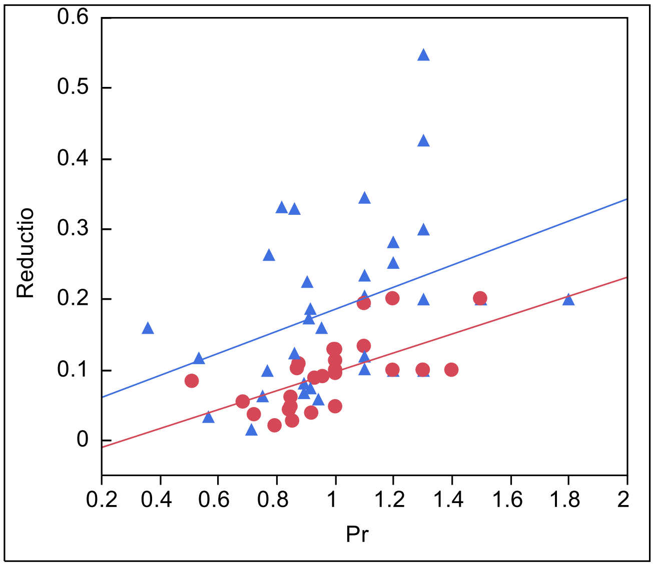
Figure 9: Thickness of Dentin Removed by Location and Instrument

It is useful to understand the relationship between the reduction in thickness and the pre-instrumentation thickness. Figure 10 shows this relationship for each location. In the first panel that represents the relationship at Point A (0.9 mm apical to bifurcation), it should be noted that the LSX line (red dots) is flatter and that the spread of dots around the line is less indicating less variability in the thickness of dentin removed by LSX. For WO values, the variability in the amount removed is more than twice that for LSX (SD = 0.114 versus 0.052) and the slope for LSX is flat ($P = 0.0834$) whereas there is a significant relationship between the thickness of dentin removed and the pre-instrumentation thickness for the WO ($P = 0.0003$). In the second panel of Figure 10, at Point B (1.8 mm coronal to the apex) there is a significant relationship in both cases ($P < .02$) and, again the spread of dots around the trend line is wider in case of WO

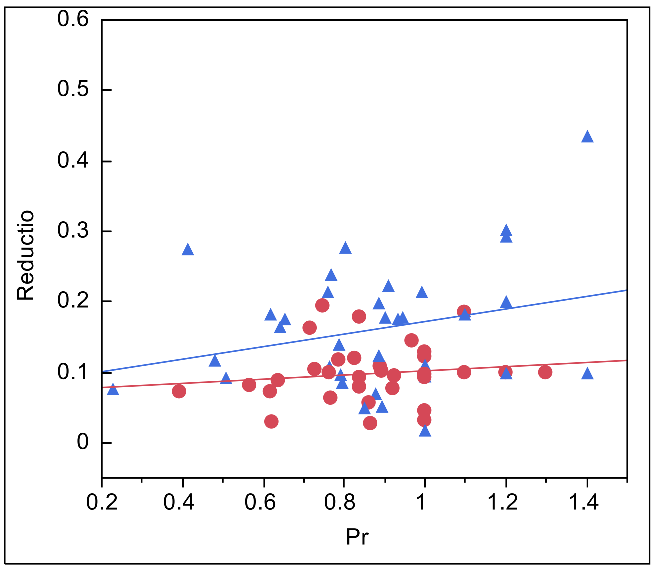
(WO SD = 0.106 versus LSX SD = 0.041). At Point C (midway between Points A and B), there is no relationship between the thickness of dentin removed and the pre-instrumentation thickness for LSX (P = 0.48) and a weak but significant relationship for WO (P = 0.0341). There is also twice the variability around the trend line in case of WO (SD = 0.083 versus 0.039). At Point D (deepest invagination), there is a weak but significant relationship in case of LSX (P = 0.0339) and a strong trend in case of WO (P < .0001). Again, there is twice the variability (SD = 0.101 versus 0.042).



Location = Point B



Location = Point C



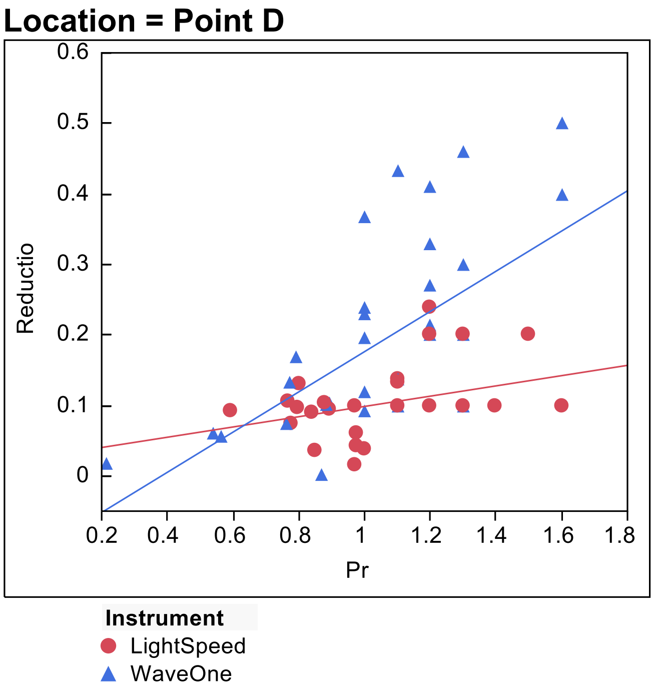


Figure 10: Relationship between the Reduction in Thickness of Dentin and Pre-Instrumentation Thickness by Location and Instrument

For LSX, there is essentially no relationship between the amount removed and the pre-instrumentation thickness (a flat trend line) and the thickness removed is much more predictable indicating less variability. For WO (blue triangles), there is a relationship between the thickness of dentin removed and the pre-instrumentation thickness (a positive trend line) and much more noise in our ability to predict how much dentin will be removed indicating more variability.

The Effect of Instrument Size

As was shown in Table 1, a number of different sizes were used for each type of instrument. It is of interest to compare the thickness of dentin removed as a function of these

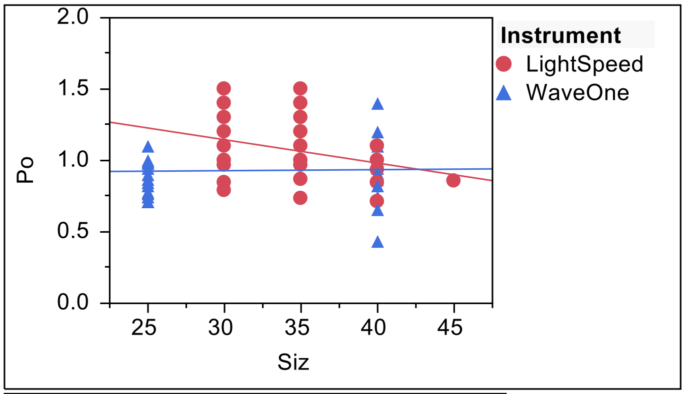
sizes. Table 9 shows each Location, Instrument and Size with the average and range of the thickness measurement and the pre-post thickness removed.

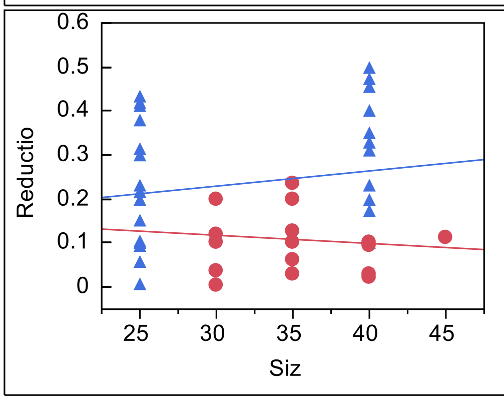
Table 9: Effect of Instrument Size

				Thickness (mm)			Removed (mm)		
Location	**Instrument**	**Size**	**n**	**Mean**	**Range**		**Mean**	**Range**	
Point A	LightSpeed	30	15	1.13	0.8	1.5	0.11	0.005	0.200
		35	14	1.10	0.7	1.5	0.13	0.029	0.235
		40	6	0.95	0.7	1.1	0.07	0.023	0.100
		45	1	0.86			0.11		
	WaveOne	25	21	0.93	0.7	1.1	0.21	0.009	0.433
		40	15	0.94	0.4	1.4	0.26	0.034	0.500
Point B	LightSpeed	30	15	1.00	0.6	1.3	0.10	0.026	0.200
		35	14	0.97	0.7	1.3	0.10	0.019	0.200
		40	6	0.79	0.4	1.0	0.12	0.061	0.200
		45	1	0.77			0.11		
	WaveOne	25	21	0.83	0.5	1.3	0.16	0.033	0.332
		40	15	0.83	0.2	1.6	0.22	0.015	0.548
Point C	LightSpeed	30	15	0.83	0.5	1.1	0.09	0.030	0.129
		35	14	0.81	0.6	1.2	0.11	0.032	0.193
		40	6	0.67	0.3	1.0	0.11	0.071	0.177
		45	1	0.84			0.03		
	WaveOne	25	21	0.76	0.4	1.3	0.14	0.018	0.435
		40	15	0.67	0.1	1.0	0.19	0.069	0.294
Point D	LightSpeed	30	15	1.04	0.7	1.5	0.11	0.038	0.200
		35	14	1.00	0.7	1.5	0.09	0.015	0.200
		40	6	0.83	0.5	1.1	0.12	0.093	0.238
		45	1	0.87			0.10		
	WaveOne	25	21	0.87	0.5	1.2	0.19	0.055	0.433
		40	15	0.89	0.2	1.2	0.21	0.002	0.500
Average	LightSpeed	30	15	1.00	0.7	1.3	0.10	0.039	0.175
		35	14	0.97	0.7	1.4	0.10	0.054	0.175
		40	6	0.81	0.5	1.1	0.11	0.071	0.169
		45	1	0.83			0.09		
	WaveOne	25	21	0.85	0.6	1.2	0.18	0.060	0.299
		40	15	0.83	0.2	1.2	0.22	0.088	0.356

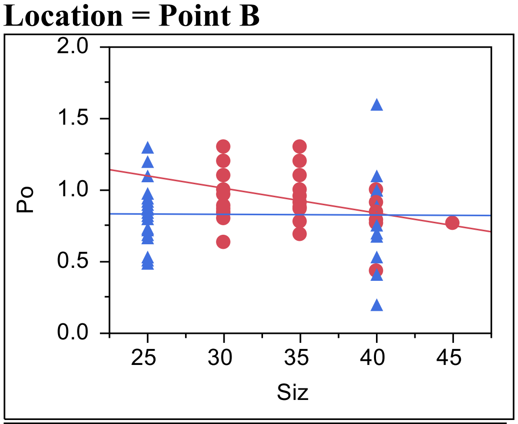
Since it may be easier to see the trends, Figure 11 shows the relationship between thickness and instrument size.

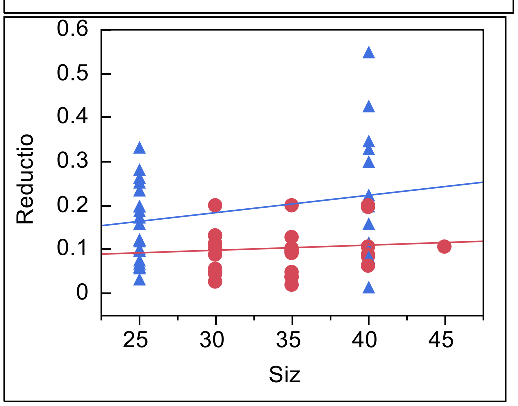
Location = Point A



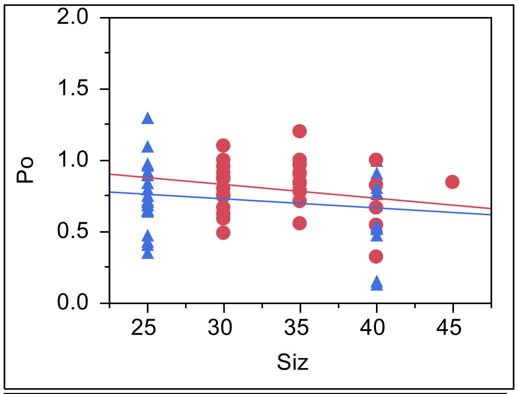


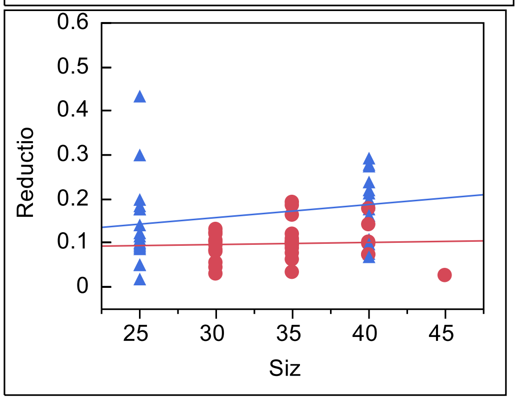
Location = Point B



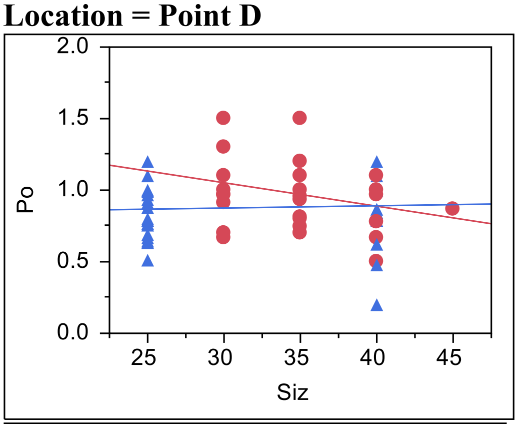


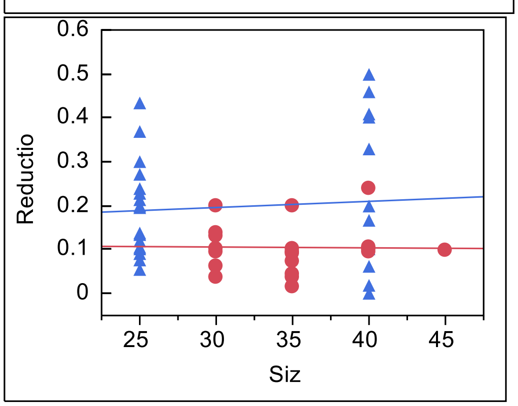
Location = Point C





Location = Point D





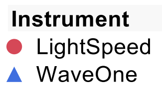


Figure 11: Effect of Instrument Size

Mean Distance of Point D (deepest invagination) from Bifurcation

The distribution of values is depicted in Figure 12. The average was 1.15 mm (SD = 0.54) but, since the distribution was not normal, a more appropriate summary would be that the median is 1.189, 50% of the values are between 1.01 and 1.255, and all of the values are between 0.065 and 3.325 mm.

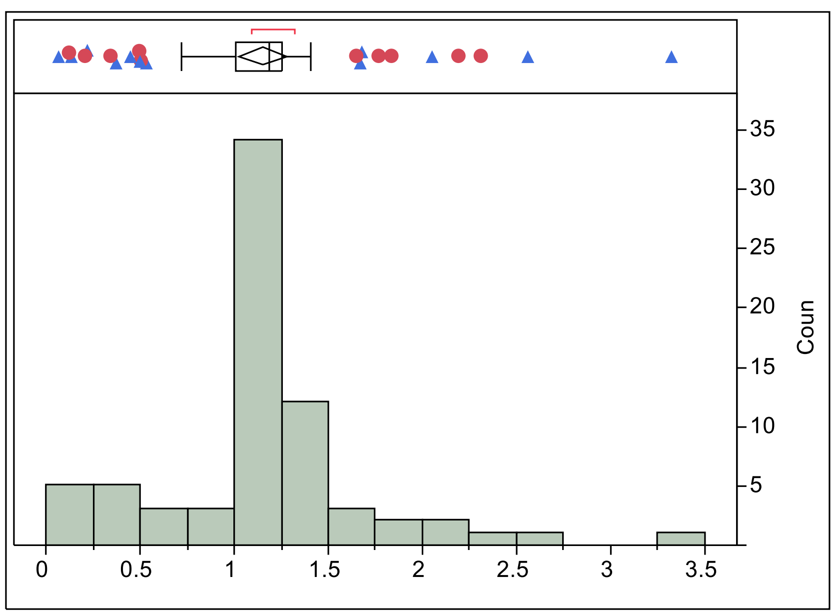


Figure 12: Distance of Point D from Bifurcation

Mean Distance of Point C from Bifurcation

The distribution of values is depicted in Figure 13. The average distance of Point C from bifurcation is 5.56 mm (SD = 1.37). Descriptively, the median is 5.5, 50% of the values are between 4.39 and 6.43, and all except three values are between 3 and 7.5 mm.

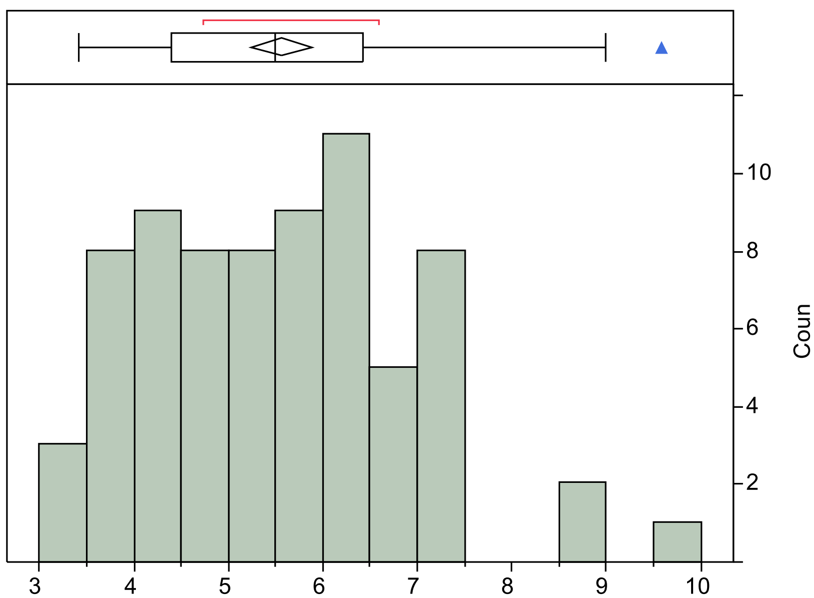


Figure 13: Distance of Point C from Bifurcation

Discussion

The aim of all dental treatment should be to prevent and treat disease without inflicting iatrogenic damage to tooth structure. Nonsurgical root canal therapy involves instrumentation that results in removal of dentin. Post-endodontic rehabilitation of teeth frequently requires post placement to reinforce a coronal restoration. Both root canal treatment and post placement remove dentinal tissue and have been implicated as a cause of VRFs. This study analyzed the dentin thickness remaining in the critical furcation groove area in the BMFP buccal root after instrumentation with two types of root canal rotary instruments.

The pre-instrumentation RDT along the furcation groove was measured at four levels. The mean RDT for 72 teeth at Point A (0.9 mm apical to bifurcation) was found to be 1.177 mm. Lammertyn et al in their anatomic study of the furcation groove of BMFP, measured the RDT at a level 2 mm apical to bifurcation and found it to be 1.17 mm (13). Katz et al evaluated RDT in BMFPs at a level 6 mm coronal to the apex and found it to be 0.99 mm (15). Similarly, Bellucci and Perrini in their study to measure the thickness of radicular dentin and cementum in BMFPs, found RDT to be 0.98 mm at a level mid-way between the cemento-enamel junction and 4 mm coronal to the apex (14). Zigo et al measured the RDT at a level 0.5 mm apical to the point of initiation of the groove and found RDT to be 0.73 mm (41). The variation in the thickness found in this study and other studies can be attributed to the difference in the corono-apical level where

these measurements were made. The measurements may also be different due to different imaging methods. Lammertyn et al used a profile projector on extracted teeth to measure RDT while Katz et al used a digitizer to take measurements on a photograph. Bellucci and Perrini used an optical microscope and Zigo et al used CBCT. Tamse et al in their morphometric study of BMFPs, measured the RDT at the point of deepest invagination of furcation groove and found RDT to be 0.81 mm (12). As measured in this study, the RDT at the deepest point of invagination was 1.083 mm.

The mean pre-instrumentation thickness in this study was not different for the two instrument groups as shown in Table 2. This allowed for equal distribution of the teeth among the two test groups. However, there was a significant difference in thickness between the locations (A, B, C & D) in a test group, but no significant difference between the four points across the two test groups. Similar difference in thickness between different locations has been shown in other studies as well (13, 14, 15). In this study, the pre-instrumentation RDT was found to be thinnest at location C, mid-groove area (0.889 mm). Other authors have reported similar findings with the RDT thinnest in the mid-groove area. Katz et al reported the RDT to be 0.78 mm (15) and Zigo et al reported the RDT as 0.63 mm in the mid-groove area (41).

Post-instrumentation, there was a significant difference in the mean thickness of the LSX group (0.942 mm) and the WO group (0.849 mm). This difference is evident across all locations (Table 5). Importantly, the post-instrumentation thickness is more variable in the WO group as compared to the LSX group. This becomes apparent with an analysis of the confidence intervals around the means in Figure 6. The confidence intervals are larger in WO group than the LSX group. The post-instrumentation thickness of dentin is thinnest at location C, which is the mid-point between locations A and B. In the LSX group this thickness is 0.791 mm and in the WO

group it is 0.727 mm. This indicates that location C, the mid-groove area, is the most critical corono-apical level across the buccal root of BMFP and should draw the attention of the clinician when treating these teeth. Zigo et al used NiTi rotary files and found the post-instrumentation thickness in the mid-groove area to be 0.39 mm (#35/0.04) and 0.30 mm (#40/0.04) (41). The difference in the RDTs between the two studies can be attributed to the fact that Zigo et al did not assign a Final Apical Size for the teeth. All their teeth were instrumented with #30/0.04, #35/0.04 and #40/0.04 and the change in thickness measured. The importance of the post-instrumentation thickness of the palatal wall of the buccal root lies in the fact that there is extensive literature to prove that as the thickness of the root decreases, it's ability to withstand stress decreases and the chances of adverse incidents like VRFs increase, resulting in tooth loss.

In 1978, Trabert et al investigated the impact resistance of teeth to simulated trauma and showed that preservation of internal tooth structure and the use of smaller posts in teeth that have been endodontically treated provide maximum resistance to fracture (44). Predisposing and iatrogenic etiological factors for VRF are reported in literature and include loss of tooth material because of caries, endodontic access cavity, and excessive root canal flaring (45). The potential for endodontically treated teeth to fracture increases proportionally with the amount of dentin removed (44). VRF in endodontically treated teeth can also be caused by restorative procedures following root canal therapy, such as canal preparation for a dowel, improper dowel, and traumatic sealing of intracanal restorations (46). A direct relationship exists between the RDT to the strength of the root (47, 48, 49). Dowel preparation not only weakens teeth (50), but the tooth capacity to withstand lateral stresses is directly proportional to the tooth wall thickness (51). Thus, preservation of sound dentin is of utmost importance (52).

The first enlightening finding in this study was the significant difference in the thickness of dentin removed by the LSX and WO instruments. The mean thickness of dentin removed by LSX was 0.104 mm, which is significantly less than the mean thickness of dentin removed by WO (0.197 mm) as shown in Figure 9 and Table 8. It was noted that this difference is evident across all the locations. Also, the thickness of dentin removed by LSX is not significantly different across all locations as compared to the significant difference seen in the dentin removed by WO across all locations. The confidence intervals around the means are also larger in WO group. This suggests that LSX removes a consistent, more predictable and smaller thickness of dentin across the length of the root, especially in the critical furcation groove area as compared to the more variable and larger thickness of dentin removed by WO. In Figure 10, comparing LSX and WO for the relationship between the reduction in thickness of dentin and the pre-instrumentation thickness reveals that as the pre-instrumentation thickness increases, dentin removed by WO also increases resulting in unnecessary removal of dentinal tissue, versus LSX that removes a consistent thickness of dentin irrespective of the pre-instrumentation thickness. Thus, it can be inferred that LSX tends to conserve dentin even as the pre-instrumentation thickness increases between different areas of the same root and between different roots as well. Similar findings are noted in the study of Zuckerman et al who established that LightSpeed rotary instruments cut all surfaces evenly, thus preventing the phenomena of cutting one surface and leaving other surfaces more or less untouched (29).

The second enlightening finding was the effect of instrument size on the thickness of dentin removed (Table 9). It is logical to think that smaller sized instruments will remove less dentin and larger sized instruments will remove more dentin but the results in this study differ and force us to think about the design of the files used to prepare the root canals. In this study,

the size of the master apical file or the Final Apical Size was dictated by the technique recommended by the respective instrument manufacturer, and the operator followed it. For LSX, this was the size that required a firm push in the final apical 4 mm to advance it to WL. For WO, if a #10 K-file was very resistant to movement, WaveOne Small file was used; if a #10 K-file moved to WL easily, was loose or very loose, WaveOne Primary file was used; or if a #20 K-file or larger went to WL, WaveOne Large file was used. It is interesting to note in Table 9 that LSX sizes #30, #35, #40 and #45 removed about the same thickness of dentin (0.10, 0.10, 0.11 and 0.09 mm respectively), once again showing that LSX technique conserves dentin. Similar observation was made by Zuckerman et al who found that root canal preparation with LightSpeed instruments to #50 does not significantly decrease the RDT (29). For WO, WaveOne Primary file with tip size of #25 and WaveOne Large file with tip size of #40 were used. Size #25 removed 0.18 mm and size #40 removed 0.22 mm of dentin. The LSX size #40 instrument removed half the thickness of dentin (0.11 mm) as compared to the WO size #40 (0.22 mm). Finally, the average size LSX file (34.03) was larger than the average file size of WO (31.25) yet removed significantly less thickness of dentin (0.104 mm) when compared to the thickness of dentin removed by WO (0.197 mm) (Table 1). These differences between LSX and WO are probably due to the difference in instrument design (LSX being non-tapered and WO is tapered) and the techniques used to determine the size of the master apical file and are consistent with the findings of other authors. Kfir et al in their in-vivo comparison used standardized K-file hand instruments and the LightSpeed instruments to compare the sizes of the first instrument with or without taper that binds to the narrow apical diameter of the root canal after coronal flaring (53). They concluded that the first non-tapered (LightSpeed) instruments to bind at the apical constriction were larger and reflected the actual narrow apical diameter of the canal better than

the tapered (K-file) instruments. Marending et al compared the apical fit of the first K-file versus the first LightSpeed LSX instrument to bind at working length after an initial crown-down preparation and found that the instruments with a flat widened tip determined the apical cross-sectional diameter better than round, tapered instruments (54). Weller et al found that there were statistically significant differences in the RDT in the apical 4 mm of mandibular incisors and mesiobuccal canals of mandibular molars following cleaning and shaping with SS Flexofiles, LightSpeed, Profile and K3 instrumentation techniques (34). They concluded that instrumentation to a larger master apical rotary file utilizing LightSpeed did not reduce RDT to any statistically significant degree.

The third enlightening fact in this study was that the thinnest dentin along the furcation groove is not at the level of deepest invagination of the furcation groove into the canal wall. The depth of invagination of the furcation groove into the canal wall was subjectively looked at in all the axial views of the root from the level of bifurcation to the root apex, and the distance of the axial slice level with deepest invagination was measured from the level of bifurcation of root. The limited field CBCT used in this study (CS 9300) had a voxel size of 90 microns (thickness of each axial slice was 90 microns) providing a thorough examination of the depth of invagination into the canal wall along the bifurcated root from the level of bifurcation to the root apex. The average distance of the deepest invagination from the bifurcation was 1.15 mm, which is close to the measurement of 1.18 mm made by Tamse et al. It is logical to assume that the RDT of the buccal root on the palatal aspect in the region of furcation groove will be thinnest at the level of deepest invagination of the groove into the canal wall. The findings in this study suggest otherwise. To date no study has measured the distance from the bifurcation to the level of thinnest dentin in the buccal root. As mentioned earlier, the RDT of the buccal root was found

to be thinnest at location C, both pre-instrumentation (0.889 mm) and post-instrumentation (LSX-0.791 mm, WO-0.727 mm), which is 5.56 mm from the bifurcation. This does not correspond to the average distance from the bifurcation to the level of the deepest invagination (1.15 mm in this study and 1.18 mm in Tamse et al's study). When treating BMFPs it is important to know the areas in the buccal root that carry high risk of perforation and fracture.

Past research has established that the RDT after root canal and post preparation is directly related to the integrity of root structure and that reducing the RDT can be detrimental to the longevity of the tooth. Further research is needed in order to define parameters for dentin removal and subsequently establish minimum values for RDT. It will be helpful for the clinician to know the minimum RDT required to resist root fracture. Studies in the past have only made recommendations based on assumptions that were not supported with research. There is no research dedicated to finding the critical value of RDT below which the risk for VRFs would increase.

These unsupported recommendations can be seen both in the endodontic and prosthodontic literature citing the minimum required RDT to be from 0.3 mm to 1 mm. Lim and Stock (22) attempted to establish a minimal RDT and speculatively set 0.3 mm as the minimal remaining RDT. McCann et al speculatively set 0.5 mm as the minimum RDT required to prevent strip perforation or weakening of the mesial root in mandibular first molars following instrumentation (23). Pilo et al in their in-vitro study to measure the RDT of BMFPs after root canal and conservative post space preparation, used 1 mm thickness of dentin to be the minimum recommended value (45). Katz et al, while studying the RDT in BMFPs after root canal and post space preparation for ParaPost, have suggested that at least 1 mm of root dentin should remain in all root aspects along its entire length after all intra-radicular procedures are completed (15).

Raiden et al used the value of 1 mm of root wall thickness as the minimum RDT to determine the instrument diameter that will not affect this measurement in maxillary first premolars when preparing post space (55). In a review of the literature, Lloyd and Palik have classified recommendations for the width of the post into three groups (56). One group is made up of authors who recommend a preparation with minimal instrumentation, and another group includes authors who propose the use of an instrument with a diameter equal to one-third of root diameter. The third group includes those authors who advise conserving at least 1 mm of dentin thickness. The biomechanical study of Caputo and Standlee suggested that at least 1 mm of root dentine should remain around the post to avoid the risk of root fracture (21). In the present study, RDT data was analysed using both 0.5 mm and 1 mm values for the minimum recommended thickness.

As shown in Table 6, for the LSX group 2.1% of teeth had the mean post-instrumentation RDT across all locations either less than or equal to 0.5 mm versus 9% of teeth in the WO group. Similarly, as shown in Table 7, for the LSX group 68.6% of teeth had the mean post-instrumentation RDT across all locations either less than or equal to 1 mm versus 80.6% of teeth in the WO group. Pilo et al measured the RDT at a level 6 mm from the cemento-enamel junction in a group of BMFP in which the point of bifurcation was within 5 mm of buccal cemento-enamel junction after instrumentation with size #40 K-file and then after post space preparation (57). The RDT (apical slice) after endodontic preparation of BMFP buccal root in the inner aspect facing the bifurcation was less than 1 mm in 53% of roots. After post space preparation, these values increased to 77% of roots. In this study at location A, 44.4% of teeth prepared with LSX and 69.4% of teeth prepared with WO had RDT $\leq$ 1 mm. Measurements from the two studies cannot be compared due to the difference in instrumentation and the group

of teeth studied. It should be noted (Table 7) that at location C, which has been previously established to be the most critical area of buccal root, 94.4% of teeth instrumented with LSX and WO had RDT $\leq$ 1 mm. Based on literature review and the results from this study, it can be stated that routine instrumentation of the buccal root of BMFPs results in thinning of root dentin below the critical value of 1 mm required to maintain the integrity of tooth structure.

Future research efforts should be directed to develop instruments and techniques that preserve the dentinal tissue. Recently a study by Kim et al was done to understand the potential relationship between design of NiTi rotary instruments and VRF (58). They used 3D finite element analysis to compare the stresses generated in the apical root dentin during rotary instrumentation in a curved canal with Profile, ProTaper and LSX instruments. Their results showed that LSX generated the lowest stresses. The ProTaper instrument with the biggest taper shaft, had stress values that approached the strength properties of dentin. They concluded that the stiffer file designs generated higher stress concentrations which raises the risk of dentinal defects that may lead to root cracking.

The digital imaging technology in the field of medicine and dentistry is advancing rapidly. Micro-computed tomography (μCT) delivers high quality images and is designed to be used exclusively for bench-top research, compared to the limited field CBCT machine that is primarily for clinical use. In the present study, micro-computed tomography (μCT) could have provided better image quality, which potentially may have increased the accuracy of the data collected (59, 60). The μCT is specifically designed for *in vitro* imaging of extracted teeth which limits their use to lab based studies. An advantage of μCT technology in comparison to the limited field CBCT technology is its ability to superimpose pre-instrumentation and post-instrumentation images of a canal. This three dimensional feature is especially useful when

comparing dentin removal relative to an area which poses an anatomical risk such as the furcation groove in MFPs. The significant cost of μCT restricts their use. Future research should be directed to repeat a similar study using a μCT and benefiting from its advantages.

The following conclusions can be drawn from this study:

1- The thickness of dentin removed from the buccal root of BMFPs in the area of furcation groove after instrumentation with LightSpeed LSX files (0.104 mm) was significantly less than the thickness of dentin removed with WaveOne files (0.197 mm).

2- LSX files remove a more predictable and consistent thickness of dentin along the length of bifurcated buccal root of BMFP, irrespective of the pre-instrumentation thickness of dentin and the file size when compared to the WO files that remove a more variable thickness of dentin.

3- The average file size for LSX was larger (0.34 mm) than the average file size of WO (0.31 mm), even though LSX removed significantly less thickness of dentin.

4- The thinnest dentin along the furcation groove is on average 5.56 mm from the bifurcation and not at the level of deepest invagination of the furcation groove into the canal wall.

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Vita

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