Variations in Apical Curvature and Constriction Morphology Affecting Electronic Readings; An *in vitro* investigation using 3D printed tooth models

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ABSTARCT

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The aim of this study was to investigate *in vitro* the effect of apical curvature and morphological variations in apical constriction on the performance of electronic root canal length measuring device (ERCLMD). For this, half-cone shaped 3D printed tooth models with varying apical curvatures and apical constriction morphologies were printed. Part 1 investigated tooth models with 0°, 15°, 30° and 45° apical curvature with group 1 having an apical constriction (AC) width of 0.3mm and group 2 with an AC width of 0.45mm. Part 2 investigated Dummer’s four types of apical constriction morphology. Ten replicas of each model was printed and the measurements were taken three times for each model. A custom made mounting device with a digital caliper was used to measure the length of the file. The ERCLMD device used was Root ZX mini (J.Morita). The model was observed under x24.0, magnification of an OPMI pico microscope (Carl Zeiss, Jena, Germany). The file tip was originally positioned at the MF and the digital caliper was calibrated to zero. Then the file was retracted coronally up the canal above the AC and slowly proceeded down towards the major foramen (MF). The lengths of the file were measured when the ERCLMD screen signaled the 0.5 mark and the apex mark. A file tip inside the canal has a negative value and a file tip beyond the MF has a positive value. Results: Part 1- For the 0.5 mark of the #30AC models and the apex mark of the #45AC models, increasing the curvature resulted in a shorter distance from the MF. For the apex mark of the #30AC models and the 0.5 mark of the #45AC models, when the apical curvature increased, the distance of the file from the MF increased. Part 2- the distance from the MF at the 0.5mark and apex mark of the tapered constriction model was longer than that of the single constriction, multiple constriction and parallel constriction models. Based on the results from both parts of the study, reading at the apex mark indicated less variation of standard deviation than at the 0.5 mark. Conclusion: Increasing the apical curvature can decrease the accuracy of the ERCLMD. In clinical situations, when faced with canals with severe root curvature, the final measurement using ERCLMD should be done after passive negotiation of the canal is achieved first. In addition to the electronic method, the radiographic method should be used as well for a more accurate working length (WL) determination. The lack of AC in

tapered constriction models might be the reason for the decreased accuracy of the ERCLMD. In cases with apical variations such as apical curvature and morphological differences of the apical constriction, the apex mark is more reliable than the 0.5 mark.

Keywords : apical curvature; Dummer constriction; Constriction morphology' ERCLMD performance

I. Introduction

Working length (WL) determination is critical for the success of endodontic treatments [1]. Root canals should be debrided and shaped throughout its entire length aiming for complete disinfection, while preventing overextension of endodontic instruments that could damage periapical tissues [2].

Using the traditional two-dimensional radiographic method alone to determine the WL has many limitations [3, 4]. A critical problem is that the major foramen (MF) usually deviates laterally from the anatomic root apex, with the length of deviation varying from 0.2 to 3.8 mm [3]. This means that the radiographic apex most often does not coincide with the actual MF, resulting in inaccurate WL determination. Anatomic superimpositions of the apex is another limitation of the radiographic method. To overcome such limitations, modern electronic root canal length measurement devices (ERCLMD) based on electrical and physical principles have been developed and are now extensively used in clinical situations. The basic assumption is that all human tissues have certain electrical properties that can be used to calculate resistance and impedance [5]. Reports on the accuracy of ERCLMDs ranges from 82 to 100%, depending on the type and measurement method of the ERCLMD [6-10].

Numerous studies have reported that anatomical variations in the apical area of the root can interfere with the accuracy of the ERCLMDs. [7, 11, 12] However, very limited studies have reported the effect of apical curvature or the morphology of apical constriction on the performance of ERCLMD. In most clinical cases, the root canal is not straight but rather curved with varying degrees of curvature. Common apical curvatures are seen in the maxillary second premolar, palatal root of the maxillary first molar, maxillary lateral incisor, mandibular central incisor, mandibular second premolar, mesio-buccal canal of mandibular first molar.

One study revealed that Raypex 5 showed 45% less accuracy in curved canals than in straight canals [13]. Another study using SEM analysis evaluated the Root ZX for its accuracy and found that error in locating the apex was significantly lower in cases with straight canals than in cases with a lateral foramen where the canal has a sharp curve [14]. Santhosh et al. [15] reported that ERCLMD accuracy was 95% accurate for mild curvature group and 80% accurate for moderate and severe curvature group. Ibarrola [16] reported that pre-flaring curved canals can increase the accuracy of EAL. On the other hand, some studies claim that root curvature does not have a significant effect on the accuracy of ERCLMDs [17, 18]. Not only is there a limited number of studies but also differences in experimental materials and designs hinders the solitary effect of root curvature on EAL. One of the biggest problem is that precedent studies used natural teeth. Using natural teeth poses many uncontrolled factors that may affect the results, obscuring the true effect of the independent variable. Moreover, most of the related studies have used destructive methods to analyze the results, such as trimming or sectioning which alters the original aspect of the apical anatomy and might result in inconsistent information regarding the position and presence of the AC [19].

To overcome such problems of natural teeth, three dimensional (3D) printed teeth models can be used. In 1987, Huang [20] used glass tubules of variable diameters immersed in saline to show that ERCLMDs measured the physical effects rather than tissue resistance, as well the influence of the size of the apical diameter in the electronic readings. Such finding means that ERCLMs can work in models that are not physically real human teeth. Computer-aided design (CAD) and 3D printing technology can be used to produce prototyped tooth models with calculated variations in apical morphology to understand the influence of the variations in the diameter of AC and the curvature of the root on the accuracy of ERCLMDs. The use of these repeatable and comparable tooth models has the potential to overcome some limitations of uncontrolled and variable anatomy of natural teeth.

Another apical variation that has not been explored regarding its effect on the ERCLMD is the morphology of the apical constriction. In 1984 Dummer [21] found that the apical constriction can be classified into four types which are: traditional single constriction, tapered constriction, multiple constriction and parallel constriction. To date, no studies on how such variations in the morphology of the apical constriction can affect the performance of the ERCLMD. However, the manual of Root Zx mini advises that since some canals have multiple constrictions, it is essential that the file be taken to the apex then returned to the apical constriction (0.5 mark). This is based on the assumption that in canals with multiple apical constrictions, the file will respond to each of the constriction down the path to the MF. Unfortunately, this is not an evidence-based assumption.

The importance of investigating the effect of apical curvature and apical constriction morphology is that clinical adjustments might be needed to be made. Working length determination, as so the word determination means, is the decision of the clinician to take the information from the radiograph and ERCLMD and conclude on the ideal end point of root canal treatment. Therefore, if root curvature or apical constriction morphology does affect the ERCLMD, clinicians must make particular adjustments to their normal WL determination routine.

This study was conducted in two parts. Part 1 investigated the effect of apical curvature and apical width on ERCLMF and part 2 investigated the effect of apical constriction variation. The aims of this study are: 1) Find the effect of apical curvature on the performance of ERCLMD in 3D-printed tooth models 2) Find the effect of the morphology of apical constriction on the performance of ERLMD.

The null hypothesis were 1) The curvature of apical constriction will not affect the performance of the ERLMD 2) The variations in the morphology of the apical constriction will not affect the performance of the ERLMD

II. Materials and methods

2.1. 3D-printed tooth models

Single-rooted tooth models were designed by Rhinoceros 3D (Robert McNeel & Associates, Seattle, WA, USA). Each model was designed as a half-coned shape to enable a direct observation of the file tip during the experiment. External dimensions were height of 21 mm, and width of 7mm at the coronal part and 2.5mm at the apical end. The internal coronal and apical diameters of the artificial canals were respectively 2 mm and 0.5 mm, with a constant taper. Ten replicas of each tooth model were printed in M3 crystal (3D systems, Rock Hill, SC, USA) at resolution of 16 µm and tolerance of ±0.001 - 0.002 inch per inch using a Projet 3600HD MAX 3D printer (3D systems, Rock Hill, SC, USA).

2.1.1. (Part 1) Apical Curvature and major foramen size

The apical curvature initiates at 2mm from the MF with a maximum curvature at 1mm from the MF. Two groups with apical constriction width of 0.3mm and 0.45mm respectively, each with four models varying in the severity of the apical curvature were designed and printed. (Fig.1)

1. Group 1 (#30 AC): #30-0 °(straight canal), #30-15 °(15° curvature), #30-30 °(30° curvature), #30-45 °(45° curvature)

2. Group 2 (#45AC): #45-0 °(straight canal), #45-15 °(15° curvature), #45-30 °(30°

curvature), #45-45 °(45° curvature)

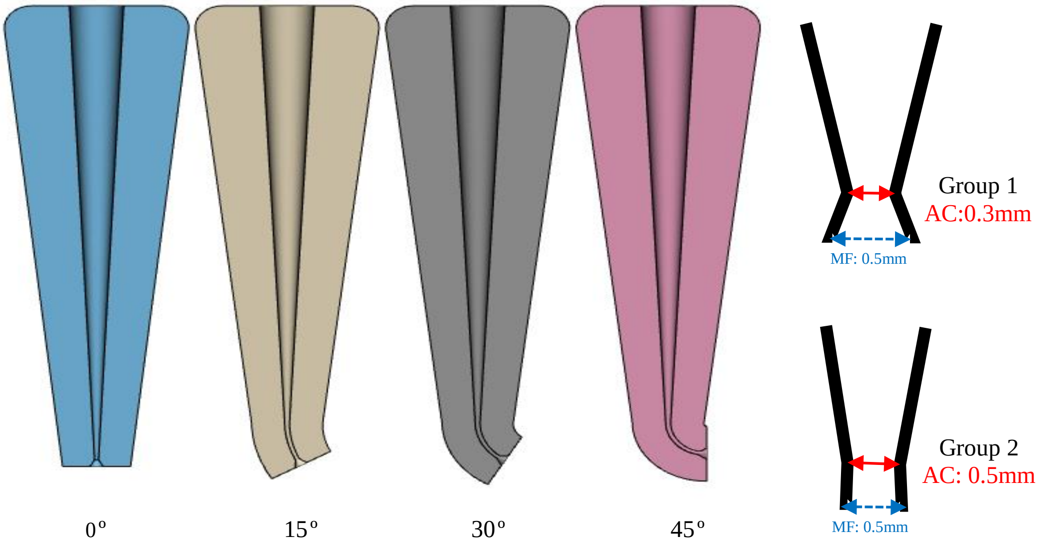

Figure 1. Tooth model designs with apical curvature.

2.1.2. (Part 2) Apical Constriction Morphology (Dummer type)

Four types of models designed with the four types of apical constriction morphology [21]. For all models except the tapered model, the AC width was 0.2mm and MF width was 0.5mm. (Fig.2.)

1. Model SC (Single Constriction): AC located at 2mm from MF.

2. Model TC (Tapered Constriction): Canal has a constant taper to the MF without AC.

3. Model MC (Multiple constriction): Three independent ACs located at 0.3mm, 0.6mm and 0.9mm from the MF.

4. Model PC (Parallel Constriction): Two ACs located at 0.3mm and 1.3mm coronally from the MF, with a constant width of 0.2mm between them.

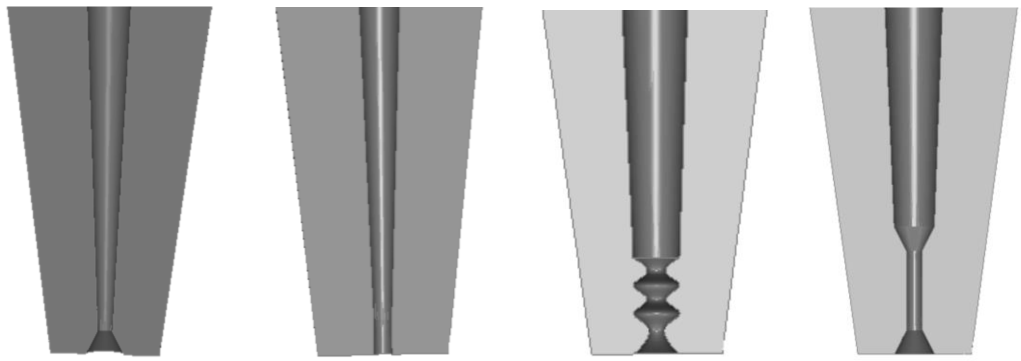

Figure 2. Tooth model designs with Dummer apical constriction morphology

2.2. Electronic measurements

The artificial models were fixed in a transparent acrylic tank filled with saline. A custom-made mounting model with a digital caliper (Fig. 3.), similar to previously described by Elayouti et al. [22] was used to measure the distances of the file tip from the MF at the 0.5mark and Apex mark. The digital caliper recorded vertical movements at 0.01 mm increments. The ERCLMD electrode and lip clip were connected respectively to the #10 K-file and to the tank. The ERCLMD was connected to the system and the file carefully positioned at the landmark MF as observed under an x24.0, magnification of an OPMI pico microscope (Carl Zeiss, Jena, Germany).

The digital caliper attached to the file was calibrated to zero. The file was retracted coronally up the canal until the 0.5 mark flashed on the ERCLMD display. The distance on the digital caliper was recorded at this point. Then, the file was slowly advanced apically until the Apex mark flashed on the ERCLMD display and the measurement on the digital caliper was recorded. A positive value indicates that the file tip was located beyond the MF, and a negative value indicates that the file tip was short of the MF. The ERCLMD device used was Root ZX mini (J.Morita, Tokyo, Japan)

Figure 3. Custom made mounting device with digital caliper.

2.3. Statistical Analysis

The associations between the positions of each EAL mark and the anatomical points of the root apex were evaluated using linear regression analysis. The standard deviation was obtained to evaluate the consistency of each EAL mark between the different tooth models. A paired t-test was performed to compare the width between 0.5 mark and the apex mark for the four different Dummer constriction models. All statistical analyses were performed using SAS statistical package version 9.4 (SAS Institute, Cary, NC, USA). P values under 0.05 were considered significant.

2.4. Terminology of Digital caliper measurement lengths

The value on the digital caliper indicates the distance (mm) of the file from the MF. Initially, the file is positioned at the MF and the digital caliper is calibrated to zero. A positive value indicates that the file is located outside of the MF. A negative value indicates that the file within the can, short of the MF. From here on the term “distance of file” refers the distance of the file tip from the MF.

III. Results

3.1.1. (Part 1) The effect of apical curvature on EAL

0.5 Mark: Figure 4 and 5 Shows that at the 0.5 mark, as the curvature increases, the distance of file increases for #30AC group. This means that the 0.5 mark appeared at a more coronal position. The average increase of distance was 0.07mm (p-value<.0001). For the #45AC group, as the curvature increased, the distance of file decreased. This means that the 0.5 mark appeared closer to the MF as the curvature increased. The average decrease of distance was 0.019mm (p-value=0.0087). The numerical values of the figure 5 are shown in Table 1.

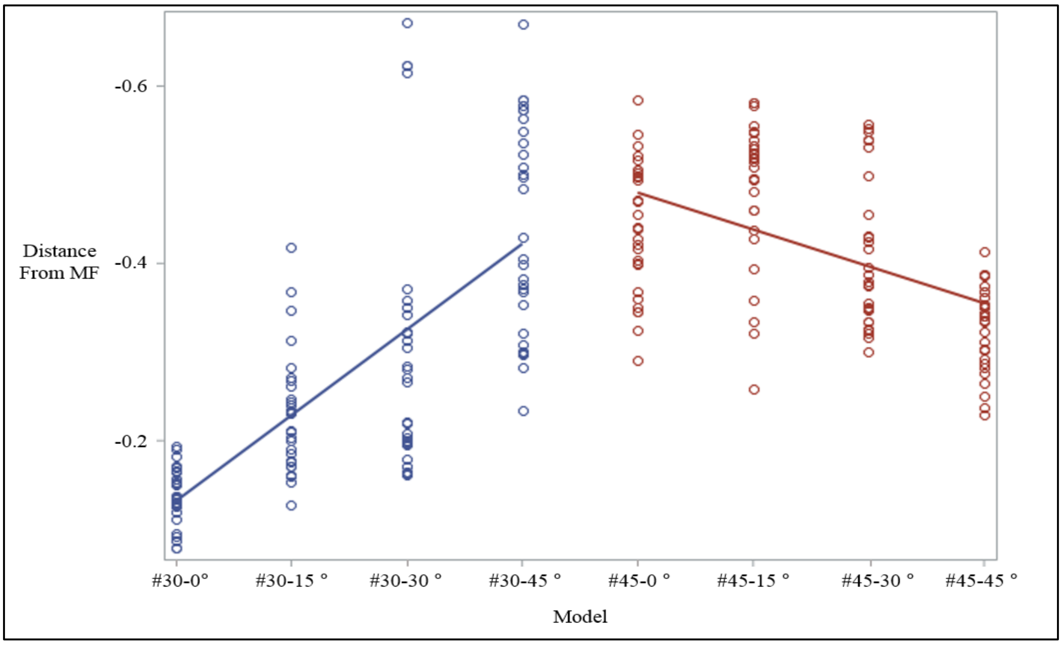

Figure 4. Scatter plot showing the distance of file at the 0.5 mark as curvature increases.

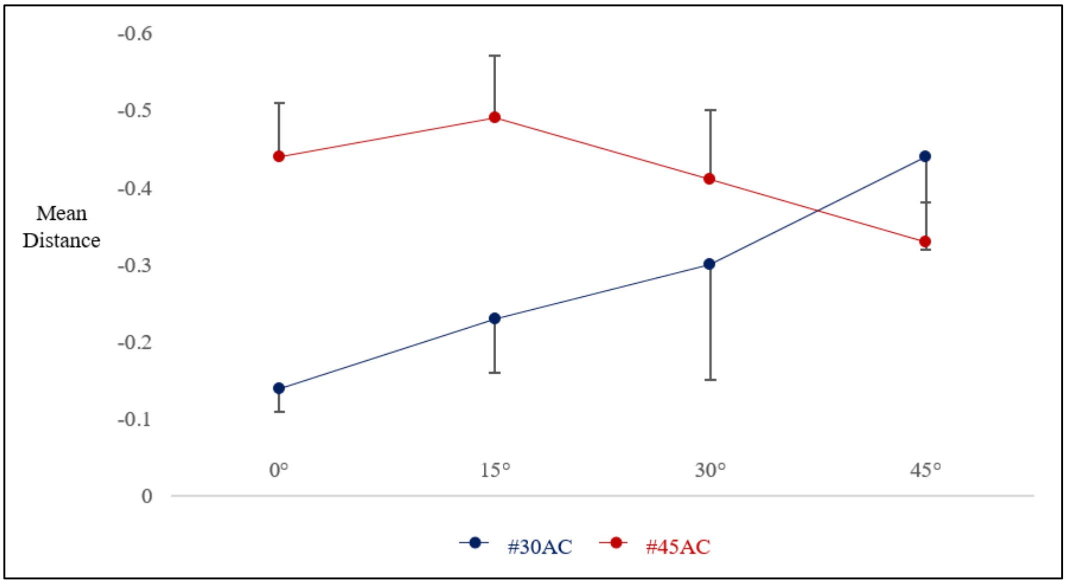

Figure 5. A mean plot of the mean distance of file at 0.5 Mark as the curvature increases.

Apex Mark: Figure 6 shows that at the apex mark, as the curvature increases, the distance of file increases for #30AC group. This means that the apex mark appeared at a position further outside the MF. The average increase of distance was 0.07mm (p-value<.0001). For the #45AC group, as the curvature increased, the distance of file decreased. This means that the Apex mark appeared closer to the MF as the curvature increased. The average decrease of distance was 0.019mm (p-value=0.0087)

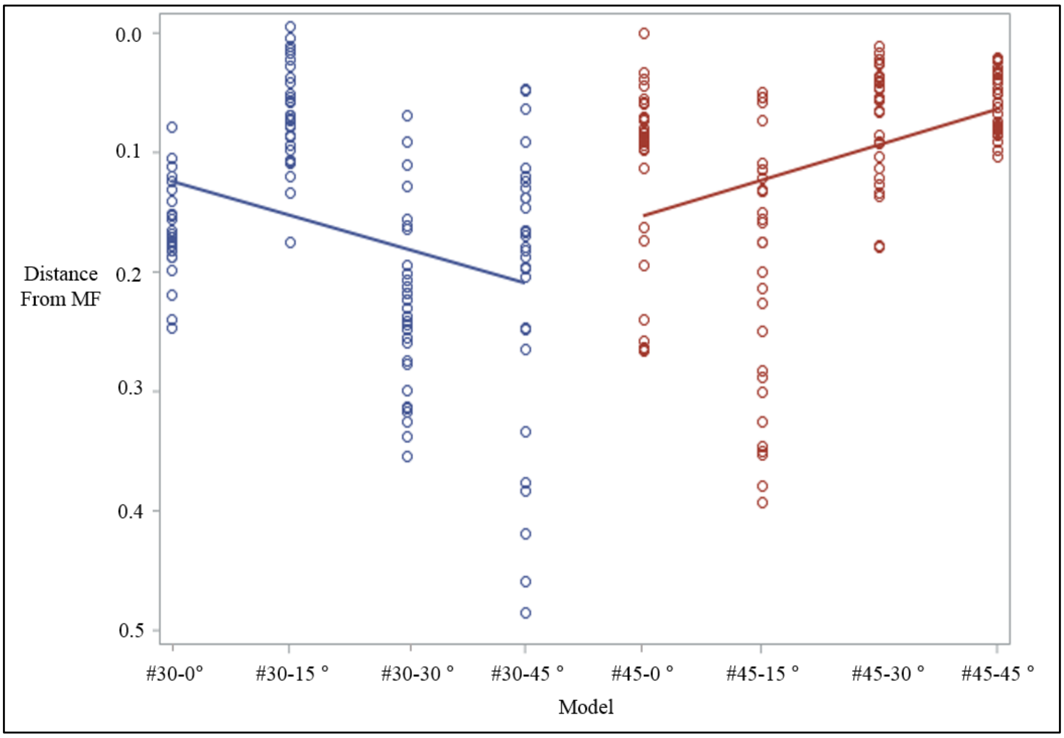

Figure 6. Scatter plot showing the distance of file at the apex mark as curvature increases.

Table 1 shows the mean distance of file and standard deviation of each tooth model at the 0.5 mark and apex mark.

	0.5 Mark Mean ± STDev	Apex Mark Mean ± STDev
#30-0	-0.14 ±0.03	0.17 ±0.04
#30-15	-0.23 ±0.07	0.07 ±0.04
#30-30	-0.30 ±0.15	0.23 ±0.07
#30-45	-0.44 ±0.12	0.21 ±0.12
#45-0	-0.44 ±0.07	0.11 ±0.11
#45-15	-0.49 ±0.08	0.20 ±0.11
#45-30	-0.41 ±0.09	0.07 ±0.05
#45-45	-0.33 ±0.05	0.06 ±0.03

Table 1. Mean distance of file and standard deviation at 0.5 mark and apex mark, for the curved models.

Figure 7 shows that at the apex mark, all models except #30-15° and #45-15°, the trend found in the scatter plot coincides with that of the mean plot graph. However, models #30-15° and #45-15° were exceptions to the general trend. This means that for #30AC group, although there was a statistically significant trend of increase in distance of file as the curvature increased, the distance at the apex mark for #30-15° was shorter. For #45AC group, although there was a statistically significant trend of decrease in distance as the curvature increased, the distance at the apex mark for #45-15° was longer. The numerical values of the figure 7 are shown in Table 1.

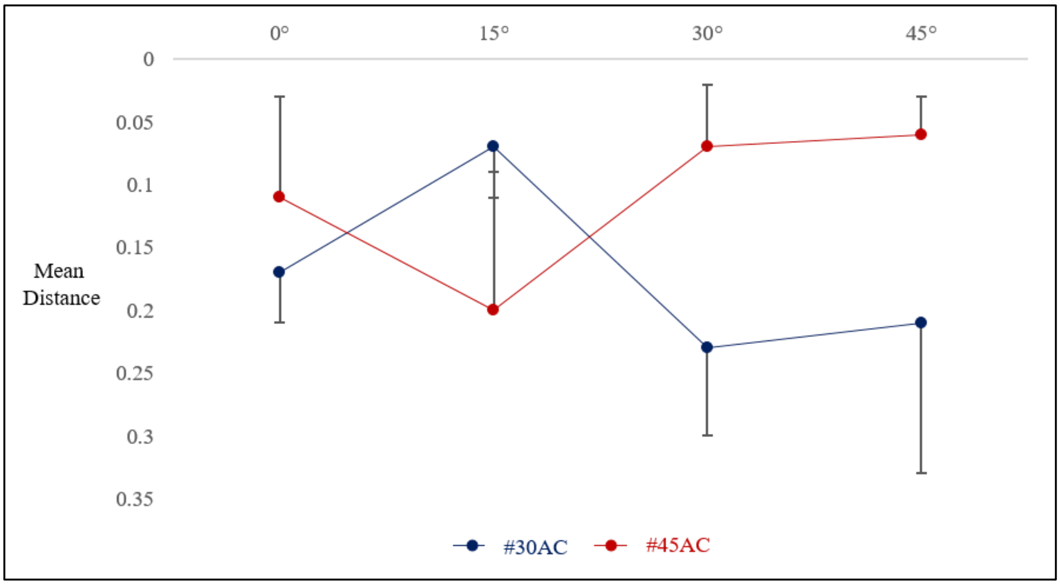

Figure 7. A mean plot of the mean distance of file at Apex Mark as the curvature increases

3.1.2 Variation of the 0.5 mark and the Apex mark

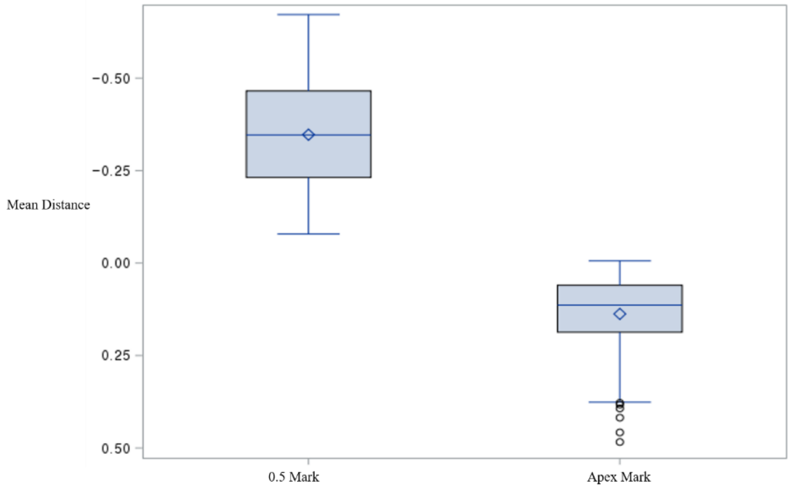

Figure 8. Box and whiskers plot showing mean distance of file at 0.5 mark and apex mark.

Figure 8 shows the variation of the 0.5 mark and apex mark. The box plot shows that the

Apex mark shows a significantly lower variation than the 0.5 mark.

3.2. (Part2) The effect of apical constriction morphology (Dummer) on EAL

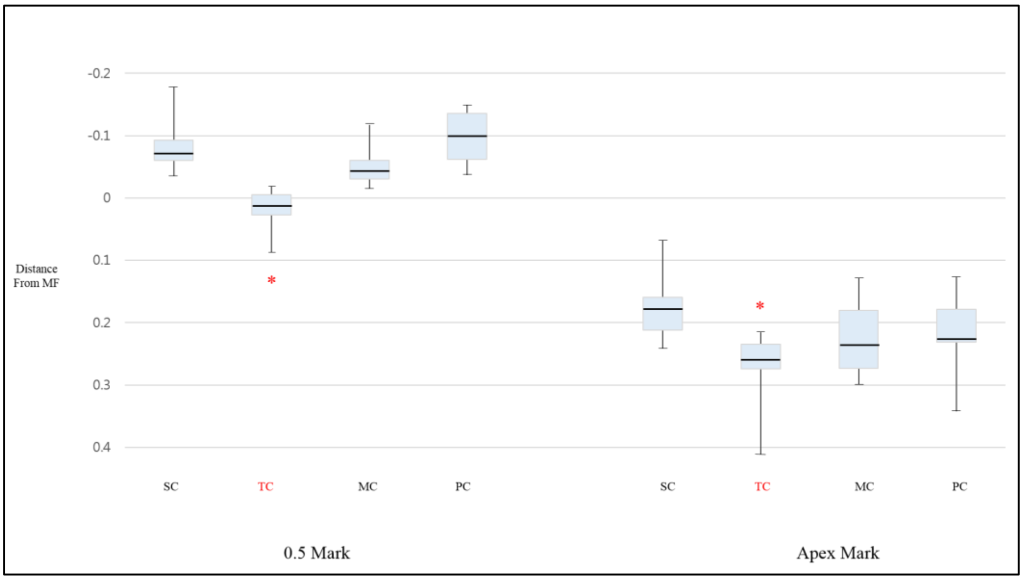

Figure 9. Box and whisker plot showing the distance of file at 0.5 Mark and Apex Mark, for the Dummer constriction models. (SC: single constriction, TC: tapered constriction, MC: multiple constriction, PC: parallel constriction)

Figure 9 shows the distance of the file at 0.5mark and apex mark for the four types of Dummer models. For both the 0.5 mark and the apex mark, the tapered constriction (TC) model was significantly longer than the SC, MC and PC models. There were no statistical differences between the SC, MC and PC models.

Table 2 shows the mean distance of file and the standard deviation at the 0.5 mark and apex mark for the Dummer constriction tooth models. The table shows that the apex Mark has a smaller standard deviation than the 0.5 mark.

	Mean distance (mm)	STDev
0.5 Mark	-0.35	0.14
Apex Mark	0.14	0.1

Table 2. Mean distance of file and standard deviation at 0.5 Mark and Apex Mark for the Dummer models.

IV. Discussion

The advantage of 3D printed models is that models with specific AC and MF can be designed and printed with as many identical replicas as needed. The 3D tooth models were designed as half-cone-shaped to enable direct observation of file movement under the microscope. The visualization of the file movements eliminates the necessity of destructive procedures and allows miniscule measurement of 0.01 mm possible. The more consistent experimental procedure and an independent measurement at each mark minimize the accumulation of errors.

In tooth, dentin and cementum work as insulators of electrical current, while tissue and fluid act as the conductive medium in the canals and apex. Although the 3D-printed tooth used in our experiment is not made of real dentin, the ERCLMD functions normally regardless of the model material. The 3D-printed tooth model, which is made of M3 crystal plastic, acts as an insulator like dentin, and the saline in the plastic tank plays the role of conducting medium. Fernando et al. [23] found that the measurement of ERCLMD is the same with *in vivo* and *in vitro* conditions. It is reasonable to say that an EAL functions properly with a 3D-printed model.

4.1. Effect of apical curvature on the length of EAL

The distance of file at the 0.5 mark in #30AC group and the apex mark of the #45AC group becomes shorter as the curvature increases. All models used in this study had an equivalent height of 21mm and a constant taper from the orifice to the AC. As the curvature of the model increases, although the height remains the same, the length of the actual canal increases. With a longer canal length, the taper from the orifice to the AC will be less significant. This means that the difference in width of the canal right prior to the AC will be less significant. The Root Zx is an impedance ratio based EAL that calculates the ratio between the impedance of the canal wall and the apical foramen [24]. In the oral cavity, this ratio between the two impedance values is known to be a constant of 0.67. When the file tip is far away from the foramen, the impedance ratio is close to 1 and as the file tip moves towards the foramen it approaches the 0.67 constant. The mark of the EAL appears within an area proximal this constant. With decreased taper, the change in ratio of the impedance becomes less significant meaning that difference in ratio of the area near the 0.67 constant becomes vaguer. This means that the zone that the EAL mark appears will be more diffuse.

However, the distance of file at the apex mark for the #30AC group increases as the curvature increases. A possible explanation of this is due to increased resistance inside the canal. Figure 10 shows that as the curvature increases, the area of the file that comes in contact with the canal increases. The custom-made mounting device with digital caliper measures the amount of movement the handle is turned. When there is no resistance, the movement of the handle will perfectly correspond to the vertical movement of the file inside the canal. However, when the file is met with resistance at the inner curve of the canal, turning the handle may not necessary result in a vertical movement of the file. Instead, there may be a brief region where the file bends without any protrusive movement until the resistance is overcome. Therefore, the measured distance of the file will appear to be longer.

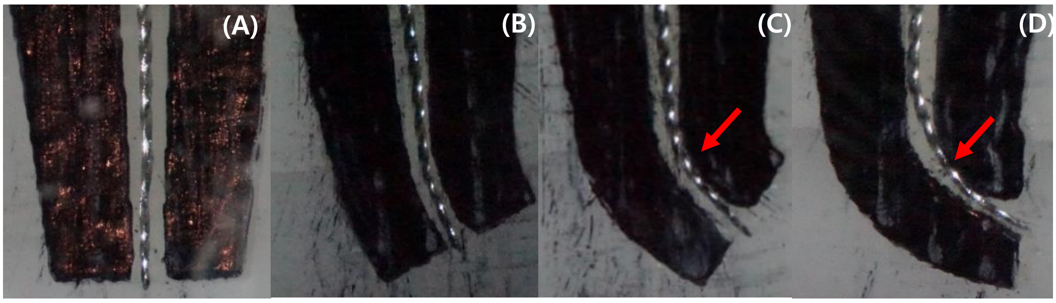

Figure 10. Microscopic view of the file position of #30AC group models. (A) #30-0° (B) #30-15° (C) #30-30° (D) #30-45°. Figure 10 (C) and (D) shows that as curvature increase the area of the file in contact with the canal increases.

In Figure 10 (B), it can be seen that when the curvature is mild such as 15° the file does not suffer any resistance. This point explains why in Figure 7, the distance of the file for model #30-15° is significantly shorter.

In Figure 7, it can be seen that the apex mark of #45-15° shows a much longer distance than model #45-30° and #45-45°. A possible reason for this phenomenon can also be explained by observing the microscopic images. All models except #45-15° required a pre-curve in order to be negotiated to the MF. Model #45-15° had only a mild curvature with a wide canal that could be negotiated with a straight file. However, although the canal could be negotiated, the file suffered additional resistance at the inner curvature and the inferior border of the MF, resulting in a longer measured distance of file. Figure 11 (B) and (C) shows that the file tip in models #45-30 and #45-45 are located at a position free from any resistance.

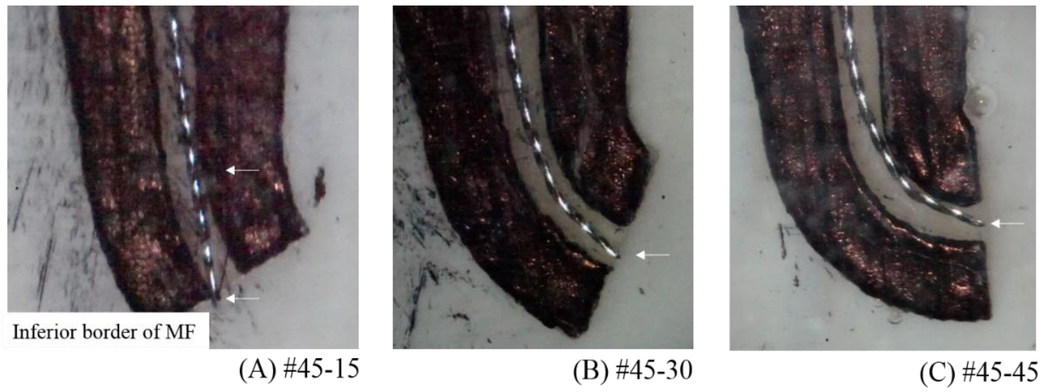

Figure 11. Microscopic image of #45AC models. (A) File meets resistance at the inner curve of the canal as well as the inferior border of the MF. (B), (C) File tip positioned near

the center of the MF.

Figure 4 shows that the length of 0.5 mark of the #45AC group increases as the curvature increases. In other words, the 0.5 mark appears at a position further down the canal, closer to the MF. This is opposite to our finding that increasing the canal curvature results in a shorter length. At this time, this phenomenon cannot be explained.

The results of this study may be limited to the exact settings of this study. In other words, if the experimental settings were different, such as a different sized file, the results might show a different trend. Therefore the results of this study cannot be generalized and applied directly to clinical situations. However an undeniable point is that the accuracy of the ERCLMD decreases when canal curvature is present. This inaccuracy may be partly due to increased resistance in curved canals, as suggested by authors of precedent studies [13, 15, 16]. Future studies with different types of ERCLMD, various file size, and foramen size etc. should be conducted to overcome the limitations of this study.

It can be seen in table 1 that the mean standard deviation for most of the models is less than 0.1. This value is quite small which proves the reliability of this study. Moreover the standard deviation is quite irrelevant in our experiment. Standard deviation is how much the result deviates from the mean. This is relevant when the mean signifies a specific "size" or amount. However, in our experiment, the value measured on the digital caliper is only a representation of the location of the file tip from the MF and not necessarily a quantifiable size.

4.2. Effect of apical constriction morphology on the length of EAL

Figure 9 shows that tapered constriction model showed a significantly longer distance at both 0.5mark and apex mark. The results of the single constriction, multiple constriction and parallel constriction models showed no statistical difference. At this point, the reason for this phenomenon cannot be explained. However the fact that all the other models had no statistical difference while the tapered model showed a significant anomaly, could suggest that the lack of constriction could result in a decrease in accuracy of the EAL.

4.3. Significance of the Apex sign

The mean standard deviation of the apex mark was smaller than that of the 0.5 mark for both part 1 and part 2. This finding suggests that the apex mark is a more reliable and stable than the 0.5 mark.

V. Conclusion

1. Increasing the curvature may decrease the accuracy of ERCLMD. This may be due to increased apical resistance.

2. In clinical situation, passive negotiation should be achieved prior to EAL length measurement. A radiographic taking should also be done to aid the clinician determine the final WL.

3. In canals with a tapered apical constriction, the accuracy of the EAL decreases.

4. The apex mark is a more stable and reliable mark even when apical variations such as apical curvature and different apical morphologies exist.

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Abstract (In Korean)

치근단 만곡과 근첨협착부의 형태가 전자근관장측정기에 미치는 영향
; 3D-프린팅 치아 모델을 이용한 *in vitro* 실험

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(지도교수 정 일 영)

본 연구의 목적은 치근단 만곡과 근첨협착부의 형태가 EAL에 미치는 영향을 반원뿔 형태의 3D-프린팅 치아 모델을 이용하여 알아보는 것이다. Part 1에서는 0°, 15°, 30° 및 45°의 치근단 만곡을 가지는 모델을 group1은 근첨협착부의 넓이가 0.3mm, group 2는 0.45mm로 제작하였다. Part2에서는 Dummer의 네가지 근첨협착부 형태로 치아 모델을 제작하였다. 각 디자인당 10개의 모델을 제작하였고 모델마다 총 세 번을 실험하였다. 전자 캘리퍼스가 장착된 자체 제작한 마운팅 기구로 근관내 파일의 움직임을 측정하였다. 마운팅 기구에 고정된 파일을 OPMI pico microscope (Carl Zeiss, Jena, Germany) x24.0 배율 확대 하 관찰하였다. 파일 끝을 MF에 위치 시킨 후 전자 캘리퍼스를 0으로 맞췄다. 다음 파일을 치관쪽으로

근첨협착부를 상방 위치까지 수직 이동 시킨 지점에서 천천히 0.01mm 단위로 손잡이를 돌려 차일을 MF쪽으로 움직인다. 이때 Root Zx mini (J.Morita, Tokyo, Japan)화면에 0.5mark와 apex mark가 나타나는 순간의 전자 캘리퍼스에서 측정된 길이를 기록하다. 음성 값은 파일이 근관 안쪽에 있는 것이고 양성 값은 근관 바깥에 위치하는 것을 의미한다. 결과: Part 1- #30AC 모델의 0.5mark와 #45AC 모델의 apex mark는 만곡이 커지면 파일 길이가 더 짧아진다. 이 뜻은 각 mark가 만곡의 증가로 더 빨리 나타난 것이다. 하지만 #30AC 이하의 근관에서는 만곡이 MF부근의 저항을 증가시켜 apex mark의 길이가 더 길게 나타났다. Part 2- 테이퍼 근첨협착부를 가진 모델의 0.5mark 와 apex mark가 단일, 평행 및 다수 근첨협착부 모델보다 유의차 있게 길게 나타났다. Part 1과 2 모두에서 apex mark가 0.5mark보다 더 적은 변이성을 보였다. 결론: 치근단 만곡이 증가하면 ERCLMD의 정확성이 떨어질 수 있다. 임상에서 심한 만곡을 가지는 치아의 근관치료를 시행할 때 파일의 저항이 느껴지지 않을 때까지 negotiate한 후 최종적으로 ERCLMD를 다시 한번 측정하는 것을 권장한다. 또한, 치근단 방사선학적 근관장 길이 측정 방법도 함께 사용하여 더 정확한 근관장 길이 설정을 해야 한다. 뚜렷한 근첨협착부가 부재한 테이퍼 형태의 근첨협착부 모델에서는 EAL의 정확성이 떨어질 수 있다. 치근단 만곡 및 다양한 치근협착부의 형태와 같은 치근단 부위의 변이가 존재할 때 Apex Mark를 사용하는 것이 보다 안정적인 근관장 길이 측정이 가능하다.

핵심 되는 말 : 치근단 만곡; 근첨협착부 형태; 전자근관장