치의과학 박사학위논문

Location of apical border of mineral trioxide aggregate plug and its effect on root development in regenerative endodontic procedure : a retrospective study

재생근관치료 시 MTA plug 하연의 위치가 치근 발달에 미치는 영향에 대한 후향적 연구

2021년 8월

서울대학교 대학원

치의과학과 치과보존학 전공

전 준 희

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이 논문을 치의과학 박사학위논문으로 제출함

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Abstract

Location of apical border of mineral trioxide aggregate plug apical and its effect on root development in regenerative endodontic procedure
: a retrospective study

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Objectives. This retrospective study investigated the effect of location of apical border of mineral trioxide aggregate (MTA) plug on root development after regenerative endodontic procedures (REP) in immature necrotic permanent teeth with or without apical periodontitis. The null hypothesis was that the location of apical border of MTA plug would have no influence on root development after REP in immature necrotic permanent teeth with or without apical periodontitis.

Materials and Methods. Clinical and radiographic records of patients who underwent REP between March 14, 2012, to February 18, 2019, in the Department of Conservative Dentistry at Seoul National University Dental Hospital (Seoul, Republic of Korea) were reviewed. Thirty-three roots of 29 individuals in cohort that underwent REP consistently according to AAE guideline were included to trace radiographic changes for the root, canal, and periapical rarefaction dimensions. Based on periapical radiographs, roots were divided into two groups depending on the location of apical border of MTA plug within whole root length: coronal group (n = 13), within the upper half; apical group (n = 20), within the lower half. Periapical radiographs standardized using ImageJ software with TurboReg plugin were used to analyze root developments. Root length, apical diameter, radiographic root area (RRA), modified RRA (mRRA), and periapical rarefaction area values were digitally measured, and root development stages were categorized according to the criteria from the previous study. Preoperative and postoperative changes in data were compared between the two groups and statistically analyzed.

Results. The average age of 29 individuals was 11 years and 10 months. No significant difference between groups was found in the distribution of age, gender, tooth type, arch location (e.g., maxilla, mandible), and preoperative root development stages ($P > 0.05$). Premolars were the most prevalent tooth type (62.1%), followed by incisors (31.0%) and molars (6.9%). Statistically significant increases in root length, RRA, modified RRA (mRRA), and decreases in apical diameter, periapical rarefaction area were observed in both groups postoperatively. However, mRRA increase ratio was significantly greater in apical group than that in coronal group at early (3 – 6 months) and late (13 – 24 months) periods respectively ($P < 0.05$). Significant changes of root development stages were observed at early period for apical group and at late period for coronal group ($P < 0.05$).

Conclusion. Within the limitation of this study, the location of apical border of MTA plug did not significantly affect radiographic measurements of root development after REP. Within the 24 months follow-up period, mRRA measurements and root development stage evaluation could track significant differences between the two groups.

Keywords : Immature teeth; Location of mineral trioxide aggregate plug; Radiographic root area; Regenerative endodontics; Root development stage

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CONTENTS

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I. Introduction

Treatment of immature necrotic permanent teeth is a challenge for dentists because of their thin root dentin, which implies a higher risk of root fracture [1]. Furthermore, their immaturity is usually accompanied by the absence of a clinical end point, known as the apical constriction. Regenerative endodontic treatment is currently accepted as a predictable treatment option for immature necrotic permanent teeth [2,3]. This approach aims to elicit the innate regenerative potential of the dentin-pulp complex. It is expected to result in root development, manifesting as apex closure, root lengthening and thickening, and ideally a positive response to vitality testing. As favorable clinical outcomes accumulated, researchers have developed updated evidence-based protocols for regenerative endodontic procedures (REP) [4,5].

Previous studies have digitally measured the radiographic outcomes of REP. The changes in apical diameter, radiographic root area, root length, and root thickness were observed [6-10]. These quantitative analyses revealed that REP allowed physiologic root development, which cannot be attained by traditional non-vital pulp therapy, e.g., apexification [11]. According to the preceding research, REP resulted in increase in root width of 25% to 35.5%, in root length of 11.3 to 14.9% [12,13], and in radiographic root area (RRA) up to 48.6% [8]. Furthermore, vitality responses have been reported in approximately 50% of the published cases [14].

American Association of Endodontics (AAE) suggested the protocol for REP in its latest version [4]. On the second appointment, the operator creates intracanal bleeding by overinstrumenting until the entire canal is filled with blood and inserts MTA plug on top of the blood clot as capping material. Mineral trioxide aggregate (MTA) is the material of choice due to its excellent biocompatibility and sealing ability [15-17]. It is recommended to place 3 mm of MTA over the blood clot, followed by a bonded restorative material. The effectiveness of a 3 mm thickness of MTA against bacterial leakage has been proven in previous *in vitro* studies [18,19].

However, the placement of MTA plug can be affected by various clinical factors (e.g., formation of blood clot, proficiency of clinicians) and MTA itself is a technique sensitive material requiring careful manipulation [20]. Therefore, it is difficult to place MTA plug in a predictable manner. Despite this versatility, no study has yet compared the clinical and radiographic outcomes of REP according to its location in the root canal, especially regarding the apical border of the MTA plug.

Therefore, this retrospective study aimed to determine whether root development after REP is affected by the location of apical border of MTA plug. This is the first retrospective study to investigate whether the location of apical border of MTA plug affected the treatment outcomes of REP. The null hypothesis was that the location of apical border of MTA plug would have no influence on root after REP in immature necrotic permanent teeth.

II. Material and Method

1. Ethics and study population

The study protocol was approved by the Institutional Review Board of Seoul National University Dental Hospital (ERI19013). Clinical and radiographic records of patients who underwent REP between March 14, 2012, to February 18, 2019 in the Department of Conservative Dentistry at Seoul National University Dental Hospital (Seoul, Republic of Korea) were reviewed.

REP cases that fulfilled the following criteria were included: immature necrotic permanent teeth with or without periapical rarefaction, teeth with healthy periodontium, and restorable teeth. Teeth with vertical root fracture or crown-root fracture, internal root resorption, or ankyloses were excluded.

2. Clinical procedures

REP was conducted consistently according to the latest AAE guideline available at the time of intervention [4]. On the first visit, local infiltration anesthesia (lidocaine hydrochloride and an epinephrine injection [1:100,000]; Huons, Sungnam, Korea) and a rubber dam were applied before opening the access cavity. Root canals were copiously irrigated with a low concentration (1.5%) of NaOCl and EDTA (17%) as advised by AAE guideline. Dried canals were medicated with calcium hydroxide paste (CleaniCal; Maruchi, Wonju, Korea) and the access cavity was filled cotton pellets and temporary restoration material (Caviton; GC, Tokyo, Japan).

In the second session of REP, local anesthesia without a vasoconstrictor (lidocaine Injection 1% 4 mL; Jeil Pharm, Seoul, Korea) was applied. After isolotaion with a rubber dam, copious irrigation was conducted in the same manner as at the first visit. After intracanal bleeding was induced in the dried canal, MTA (ProRoot MTA; Dentsply, Tulsa Dental, Tulsa, OK, USA) was placed on the coagulated blood to form a plug. The access cavity was temporarily restored in the same manner but with wet cotton pellets. Composite resin restoration was done at least 24 hours later.

3. Clinical data

Age, gender, tooth type, arch location, etiology, preoperative clinical symptoms and signs, pulpal and periapical diagnoses, intraoperative factors, follow-up period, and clinical outcomes (e.g., resolution of symptoms, regaining of vitality, and discoloration) were recorded. Clinical diagnoses of the pulpal and periapical tissue were made according to 2013 AAE diagnostic guideline [21].

4. Radiographic data

Preoperative, postoperative, and follow-up periapical radiographs were collected to trace radiographic changes for the root and canal dimensions, periapical status, and root development stage, retrospectively. Analysis was made independently at early (3 - 6 months), intermediate (7 - 12 months), and late (13 - 24 months) period.

4.1 Mathematical standardization of periapical radiographs

Each patient's radiographs were saved in the JPEG format. They were standardized and digitally measured using ImageJ software (version 1.52; National Institutes of Health, Bethesda, MD, USA) and TurboReg plugin (Biomedical Imaging Group, Swiss Federal Institute of Technology, Lausanne, VD, Switzerland). TurboReg plugin was applied to compensate for any dimensional differences between images caused by the absence of an individual x-ray aiming device (Fig. 1). All the images were modified in automatic mode to eliminate any possible investigator bias. Of the 5 types of distortion algorithms, "affine" was chosen to translate, rotate, shear, skew, and enlarge or reduce the source image using landmarks on the target image. This required 3 landmarks on the source image and target image, so that the mean square difference between these 2 images could be minimized. The most selected landmarks were the mesial and distal CEJ. Other reliable landmarks were the margin of the restoration and the transitional line angle of the anterior teeth [6].

4.2 Location of apical border of MTA plug

The location of apical border of MTA plug was determined on a periapical x-ray taken on the day the plug was placed in the canal (Fig. 2). Two lines were drawn: one line projecting from the apical border of the MTA to the outer surface of the root, and the other connecting the mesial and distal CEJ. The distances of these 2 lines at the mesial and distal root surface were averaged and designated to be the location of the apical border of the MTA plug.

According to the location of apical border of MTA plug, 33 roots were divided into 2 groups. A root was designated as belonging to the coronal group if the apical border of its MTA plug was located within the upper half of the root, and as belonging to the apical group if it was in the lower half of the root. Apical diameter, root length, radiographic root area (RRA), and the size of the periapical rarefaction were measured to evaluate treatment outcomes. To quantify the actual hard tissue growth that took place under the MTA plug, a modified method of measuring RRA was suggested in this study (Fig. 3). Unlike RRA which includes whole dentin area below CEJ, modified RRA only includes dentin area below MTA plug. All the measurements were made using the preset scale of the software in triplicate by a single observer at 1-week time interval. The average of each set of 3 measurements was recorded and the intraclass correlation (ICC) test was performed.

4.3 Apical diameter measurement

Apical diameter was measured according to the previous study of Li *et al*. using the straight-line tool, crossing the radiographic apical foramen (Fig. 3A) [7]. Apical diameter decrease ratio(%) was calculated as follows:

$$\frac{(\text{preoperative diameter} - \text{postoperative diameter})}{\text{preoperative diameter}} \times 100$$

4.4 Root length measurement

Root length was determined as the average length of 2 straight lines drawn from the CEJ to the radiographic root apex at the mesial and distal sides (Fig. 3B). Previous study pointed out that measurements based on standardized images could be challenging in multi-rooted teeth [8]. To overcome this challenge, a straight line from the midpoint between the mesial and distal CEJ to the furcation was drawn. This line served as the distal and mesial borders for mesial and distal roots, respectively (Fig. 4). Root length increase ratio(%) was calculated as follows:

$$\frac{(\text{postoperative root length} - \text{preoperative root length})}{\text{preoperative root length}} \times 100$$

4.5 Radiographic root area measurement

To assess the amount the growth in root dentin, RRA was measured according to the previous study using the polygon selection tool [8]. The root area below a straight line between the mesial and distal CEJ was outlined from the surrounding periodontal environment (Fig. 3C). The corresponding pulpal space was measured and subtracted from the premeasured root area (Fig. 3D). RRA increase ratio(%) was calculated as follows:

$$\frac{(\text{postoperative RRA} - \text{preoperative RRA})}{\text{preoperative RRA}} \times 100$$

4.6 Modified radiographic root area measurement

Instead of measuring the entire dentin surface and canal space below the CEJ, only the root dentin area and canal space below MTA plug were measured (Fig. 3E, 3F). And their difference was defined as mRRA. mRRA increase ratio was calculated as described above.

4.7 Periapical rarefaction area measurement

Periapical rarefaction area was quantified using the freehand selection tool. Any periapical rarefaction area was delineated from the surrounding normal bone structure and outlines of the root dentin (Fig. 3G). The decrease ratio of periapical rarefaction area(%) was calculated as follows [22,23]:

$$\frac{(\text{preoperative rarefaction area} - \text{postoperative rarefaction area})}{\text{preoperative rarefaction area}} \times 100$$

4.8 Root development stages

Root development stages at each follow-up were determined by the criteria suggested in previous studies [24,25]: stage 1, less than 1/2 of root formation with open apex; stage 2, 1/2 root formation with open apex; stage 3, 2/3 of root formation with open apex; stage 4, nearly complete root formation with open apex; stage 5, mature root. Stages 1 to 4 were an immature apex, and stage 5 was a mature apex. Root development stages were tracked down and compared between groups and between tooth types, too.

5. Statistical Analysis

Data were recorded and organized using Microsoft Excel® (Microsoft Corp., Redmond, WA, USA). SPSS (IBM Corp. Released 2017. IBM SPSS

Statistics for Windows, Version 25.0. Armonk, NY: IBM Corp. USA) was used to analyze the data pool. Kruskal-Wallis test and Mann-Whitney test were used to analyze differences of demographic factors, clinical factors, and radiographic measurements between the two groups. Frequency tests and Mann-Whitney test were used to compare root development tendency between groups and between tooth types. The distribution of each tooth type was analyzed by Kruskal-Wallis test. The significance level was set at $P < 0.05$. Intraclass correlation coefficients (ICCs) were calculated on each data set using reliability analysis in SPSS.

III. Results

Thirty-three roots from 29 patients were included in the study. The patients' demographic data are presented in Table 1. The patients consisted of 16 girls and 13 boys, with a mean age of 11 years and 10 months (range, 9 years and 5 months to 16 years and 5 months). 10 teeth were maxillary teeth (34.5%), and 19 teeth were mandibular teeth (65.5%). Premolars were the most prevalent type of tooth (62.1%; $n = 18$), followed by incisors (31.0%; $n = 9$) and molars (6.9%; $n = 2$). Every observed immature premolar was suspected to have lost its vitality due to infection caused by fracture of dens evaginatus. Immature incisors had lost their vitality mostly because of trauma (7 cases out of 9), and molars due to dental caries and unknown reason, respectively. Every root was in either stage 3 or 4 root developmental stages before treatment begun. Demographic factors including patients' age, gender, tooth type, arch location (maxilla or mandible), and preoperative root development stage showed similar distributions in both coronal and apical groups ($P > 0.05$, Table 1).

Every tooth was diagnosed as having necrotic pulp, except for 4 teeth that had received emergency treatment before the patients presented to our clinic. Symptomatic apical periodontitis (44.8%; $n = 13$) was the most prevalent periapical diagnosis, followed by chronic apical abscess (31.0%; $n = 9$), asymptomatic apical periodontitis (20.7%; $n = 6$), and acute apical abscess (3.4%; $n = 1$). On the first visit, 23 patients complained of various degrees of symptoms (e.g., pain on percussion, palpation, and biting; mobility; or gum boil). Six patients did not exhibit any symptoms. In the second session of REP, bleeding induction was done in 27 teeth, 25 of which showed significant bleeding 3 – 4 mm below the CEJ. Two teeth failed to present visible blood clot, and it was not clearly stated whether bleeding induction was tried in the 2 remaining cases.

The locations of apical border of MTA plug in both groups are shown in Fig. 5. It revealed significant difference between the coronal (41.5 ± 4.9, $n = 13$) and apical (64.37 ± 13.8, $n = 20$) groups ($P < 0.05$). Since the radiographic images were measured by a single observer, ICC testing was performed to assess the reproducibility of each measurement set. The ICCs were over 0.995, which suggested that the measurements made by the observer were reliable over time.

Postoperative radiographic outcomes are summarized in Table 2. Root development stages in each follow-up period were tracked (Fig. 6) and sub-plotted according to tooth types (Fig. 7). Summaries of entire cases are available in Table 3 and Table 4.

1. Early period (3 to 6 months follow-up)

All teeth showed improvement or resolution of clinical symptoms 3 – 6 months after REP. Within this period, most teeth were free of symptom, and vitality was regained in one case. Four teeth exhibited coronal discoloration after treatment, and they all belonged to coronal group.

The increase ratio of root length, RRA, and the decrease ratio of apical diameter and periapical rarefaction were compared between the coronal and apical group. No statistically significant difference was found between two groups ($P > 0.05$). However, a comparison of mRRA increase ratio revealed greater root hard tissue growth in the apical group ($P < 0.05$). In this period, significant changes in root development stages occurred only in apical group ($P < 0.05$, Fig. 5).

2. Intermediate period (7 to 12 months follow-up)

Each tooth was free of symptom except for one tooth with pain on percussion. Two teeth regained vitality. Coronal discoloration was observed in seven teeth, six of which were in the coronal group. Changes in apical diameter and radiographic outcomes were not significantly different between the two groups ($P > 0.05$). Also, overall root development stages in both groups did not change significantly from the previous evaluation ($P > 0.05$). Notably, premolars in apical groups showed significant change in root development stages in this period ($P < 0.05$, Fig. 7).

3. Late period (13 to 24 months follow-up)

In the late period, every tooth was symptom-free, and five teeth regained vitality. Coronal discoloration was frequently observed in roots with coronally located MTA plugs. In this period, coronal group exhibited significant changes in root development stages ($P < 0.05$). On the other hand, the root development stages of apical group did not differ from the previous evaluation ($P > 0.05$). Notably, teeth that had undergone REP at earlier root development stages (e.g., stage 3) showed significant changes in RRA increase (%) and periapical rarefaction resolution in this period ($P < 0.05$) regardless of the MTA plug apical location. Incisors in both groups and premolars in coronal group showed significant changes in root development stages in this period ($P < 0.05$). Meanwhile, radiographic root changes did not show any significant differences between the 2 groups ($P > 0.05$), except for significantly higher mRRA increase ratio in apical group ($P < 0.05$).

IV. Discussion

Many studies have quantified the radiographic outcomes of REP by various measures such as apical diameter, radiographic root area, root length, and root thickness [6-10]. However, the possible consequences of the location of MTA plug have not been studied yet.

The location of apical border of MTA plug was notably diverse, even though all clinicians tried to follow the AAE guideline. This can be explained by three reasons. First, the amount of blood clot was not uniform. Individual factors such as blood pressure or pathological factors such as the degree of inflammation of the pulp and the periapical tissue might have affected blood clotting. Second, a collagen matrix was used only in one case. This might have induced uncontrolled delivery of MTA into the root canals [26]. Finally, clinical variations were induced from the simple fact that multiple clinicians participated in this study. Moreover, evident intracanal bleeding was not induced in 2 cases, which is one of the complications during REP [27].

The success of REP was assessed by the degree to which the following three goals were achieved in each case. The primary goal was the elimination of clinical symptoms and manifestation of bony healing. Both were fully accomplished in every case during 3 – 6 months follow-up. The secondary goal was increased root wall thickness and/or increased root length. Measurements of the root length and RRA revealed that various degrees of hard tissue growth were achieved. However, the estimated radiographic change ratios were lower than those reported in previous studies [6,8,12], because of the relatively short follow-up period. Finally, the goal of REP is to regain a positive response to the vitality testing. This is an especially important indicator since it reflects the development of immunocompetent vital pulp tissue and normal protective nociception [4]. Regaining of vitality has been reported in approximately 50% of the published cases [14]. Vitality was recovered only in 17.2% in this study.

As for acquisition of the serial radiographs of a single individual, it is important to maintain a uniform angulation of x-ray beam. Because of rapid cranio-skeletal development of young patients, it is difficult to apply customized radiographic jig. Therefore, post-acquisition standardization of images is needed. For digital measurements and standardization, the ImageJ software and its TurboReg plugin were used. The mechanism of the TurboReg plugin is based on the mathematical coordination of 2-dimensional images. It minimizes any dimensional changes that might have been incorporated into periapical x-ray due to different angulations at each visit.

In this retrospective study, radiographic root changes, including apical diameter, root length, RRA, and periapical rarefaction area did not exhibit any significant differences between the coronal and apical groups regardless of the location of apical border of MTA plug. Flake *et al*. suggested that the RRA is a reliable method to measure the amount of hard tissue growth after regeneration treatment [8]. In our study, modified version of RRA was proposed. Unlike RRA, which includes the entire root area under the CEJ, the mRRA was calculated by subtracting the canal space from the root dentin area below the MTA plug, exclusively. This modification allowed more focused interpretations of actual hard tissue growth for two reasons. First, it can be reasonably assumed that the root dentin area above the MTA plug would not change. Secondly, it prevented bias caused by dentin removal at the time of the final restoration.

The results showed a greater increase of mRRA in the apical group in the early and late periods. This finding can be interpreted as suggesting that more apically positioned MTA plug is beneficial for hard tissue growth. However, this attempt is at odds with original intention of REP, the final goal of which is to obtain regeneration of healthy pulp-dentin complex. Although coronal placement of MTA plug resulted in small amount of hard tissue growth, it allowed maintenance of canal space and ingrowth of vital tissue.

Earlier root maturation was observed in apical group. Apex closure is an important part of root maturation. According to Cvek *et al.*, root development accompanies not only quantitative growth of root length but also conical maturation of apex [25]. In this study, decrease of radiographic apical diameter and changes in root development stages shared similar patterns: coronal group showed significant changes at late period whilst significant changes were observed during early period in apical group. Considering that degrees of root lengthening and apex closure are the two decisive factors to determine root development stage, our results can be logically validated.

Coronal discoloration is known as the most widespread clinical complication after REP, and it was in this study, too [27]. Eight out of 29 cases exhibited postoperative coronal discoloration, and seven of whom belonged to the coronal group. To prevent the discoloration, it is recommended to allow enough space below CEJ. Apical placement of MTA plug is beneficial in this respect. However, it is still against the original intention of REP and alternative measures should be considered to avoid postoperative discoloration [4]. From this study, the apical placement of MTA plug could be considered only for cases in which esthetics is concerned or a post insertion is necessary.

Therefore, within the limitations of this study, it is concluded that the apical placement of MTA plug can exhibit comparable treatment outcome after REP to coronal placement. However, this approach may impede the ingrowth of vital tissue into the canal space compared to the coronal placement. As for future studies, long term observation over 24 months of larger patient pool with controlled demographic and clinical factors is required.

V. Conclusion

Within 24 months follow-up, it turned out that the location of apical border of MTA plug had no influence on clinical and radiographic outcomes after REP. All the observed cases exhibited remission of periapical rarefaction and continuing root development after REP. Furthermore, modified RRA was devised in this study to focus on the actual root growth below MTA plug. Although the apical placement of MTA plug promoted earlier root apex maturation and greater increase in mRRA, it is possible that this approach limits the amount of vital tissue ingrowth compared to the coronal counterpart.

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Table 1. Demographic data of 29 individuals

	Age (year)	Gender		Tooth type			Arch location		Preoperative Root development stage	
		Male	Female	Incisor	Premolar	Molar	Maxilla	Mandible	Stage 3	Stage 4
Coronal group (n = 13)	13.0	8	5	3	10	0	4	9	4	9
Apical group (n = 16)	10.9	5	11	6	8	2	6	10	5	11
P values	0.863	0.170		0.846			0.963		0.785	

P values < 0.05 indicate significantly different distribution between coronal and apical groups.

Table 2. Postoperative radiographic outcomes of 33 roots (Mean ± standard deviation (Median)).

		Apical diameter decrease ratio (%)	Root length increase ratio (%)	RRA increase ratio (%)		PAR decrease ratio (%)	Average follow-up period (months)
				Flake *et al.*, 2014[16]	Modified method		
Early period (3-6 months)	Coronal	30.6 ± 17.4 Ab (26.3)	3.2 ± 6.9 Aa (0.7)	5.7 ± 8.0 Aa (2.9)	9.7 ± 6.3 Bb (7.7)	69.1 ± 21.8 Aa (81.5)	4.5 ± 1.3 (5.0)
	Apical	24.2 ± 13.5 Ac (28.1)	6.5 ± 6.8 Aa (4.8)	9.1 ± 13.7 Ab (7.6)	31.1 ± 32.4 Ab (32.0)	62.4 ± 26.6 Aa (64.6)	
Intermediate period (7-12 months)	Coronal	42.7 ± 18.1 Ab (50.2)	5.6 ± 10.1 Aa (2.0)	11.3 ± 12.8 Aa (8.1)	22.3 ± 13.3 Aa (20.0)	80.9 ± 18.0 Aa (84.8)	9.8 ± 1.8 (10.0)
	Apical	45.3 ± 16.4 Ab (48.0)	5.0 ± 6.8 Aa (6.8)	10.0 ± 18.9 Ab (12.2)	31.6 ± 20.6 Ab (41.1)	75.7 ± 20.0 Aa (74.8)	
Late period (13-24 months)	Coronal	60.2 ± 25.2 Aa (63.4)	5.3 ± 5.8 Aa (5.0)	12.3 ± 11.0 Aa (6.9)	25.4 ± 13.6 Ba (22.3)	88.2 ± 18.7 Aa (96.6)	18.9 ± 3.9 (20.0)
	Apical	61.8 ± 17.1 Aa (56.7)	7.1 ± 7.5 Aa (6.2)	13.6 ± 17.3 Aa (4.0)	55.1 ± 22.6 Aa (54.2)	88.4 ± 11.8 Aa (91.8)	

Different uppercase superscripts indicate a significant difference between groups within the same follow-up period.
Different lowercase superscripts indicate a significant difference between periods within the same group.
Significant at $P < 0.05$.
RRA, radiographic root area; *PAL*, periapical rarefaction.

Table 3. Summary of clinical findings of 29 individuals

Case No.	Groups	Age	Gender	Tooth type	Arch location	Etiology	Pulpal diagnosis	Periapical diagnosis	Bleeding induction	EPT response	Coronal discoloration	Follow-up period
1	Coronal	11Y5M	Female	Premolar	Mn	DE	Pulpal necrosis	Symptomatic apical periodontitis	(+)	Unknown	(+)	1Y3M
2	Coronal	16Y8M	Male	Premolar	Mn	DE	Pulpal necrosis	Chronic apical abscess	(+)	Unknown	(-)	1Y2M
3	Apical	9Y10M	Female	Premolar	Mn	DE	Pulpal necrosis	Symptomatic apical periodontitis	(+)	(+)	(-)	1Y10M
4	Coronal	13Y1M	Female	Incisor	Mx	Unknown	Pulpal necrosis	Chronic apical abscess	(+)	(+)	(-)	1Y10M
5	Coronal	12Y4M	Male	Incisor	Mx	Trauma	Pulpal necrosis	Asymptomatic apical periodontitis	(+)	(-)	(-)	1Y8M
6	Coronal	10Y11M	Male	Incisor	Mx	Trauma	Pulpal necrosis	Asymptomatic apical periodontitis	(+)	(+)	(+)	1Y7M
7	Apical	9Y11M	Female	Premolar	Mn	DE	Pulpal necrosis	Symptomatic apical periodontitis	(+)	Unknown	(+)	1Y1M
8	Coronal	11Y5M	Male	Premolar	Mn	DE	Pulpal necrosis	Symptomatic apical periodontitis	(+)	(+)	(+)	1Y9M

9	Coronal	12Y7M	Male	Premolar	Mn	DE	Pulpal necrosis	Symptomatic apical periodontitis	(+)	(+)	(+)	1Y11M
10	Apical	16Y5M	Female	Incisor	Mx	Trauma	Pulpal necrosis	Chronic apical abscess	(+)	Unknown	(-)	0Y10M
11	Coronal	12Y4M	Male	Premolar	Mn	DE	Pulpal necrosis	Chronic apical abscess	(+)	Unknown	(-)	1Y4M
12	Apical	13Y6M	Male	Premolar	Mn	DE	Pulpal necrosis	Chronic apical abscess	(+)	Unknown	(-)	1Y1M
13	Apical	7Y10M	Female	Molar	Mn	Unknown	Previously initiated therapy	Asymptomatic apical periodontitis	(+)	Unknown	(-)	1Y11M
14	Coronal	12Y5M	Male	Premolar	Mn	DE	Pulpal necrosis	Symptomatic apical periodontitis	(+)	Unknown	(-)	1Y11M
15	Apical	12Y1M	Female	Premolar	Mn	DE	Pulpal necrosis	Symptomatic apical periodontitis	(+)	Unknown	(-)	0Y5M
16	Apical	10Y5M	Male	Incisor	Mx	trauma	Previously initiated therapy	Asymptomatic apical periodontitis	(+)	Unknown	(-)	1Y11M
17	Apical	13Y0M	Female	Premolar	Mx	DE	Pulpal necrosis	Asymptomatic apical periodontitis	Unknown	Unknown	(-)	1Y7M
18	Apical	11Y2M	Male	Premolar	Mn	DE	Pulpal necrosis	Chronic apical abscess	(+)	Unknown	(-)	1Y2M

19	Coronal	12Y4M	Male	Premolar	Mn	DE	Pulpal necrosis	Chronic apical abscess	(+)	(-)	(-)	1Y1M
20	Apical	9Y5M	Female	Molar	Mn	Caries	Pulpal necrosis	Symptomatic apical periodontitis	(+)	Unknown	(-)	1Y0M
21	Apical	10Y3M	Female	Incisor	Mx	Caries	Pulpal necrosis	Asymptomatic apical periodontitis	(+)	(-)	(-)	0Y11M
22	Coronal	19Y4M	Female	Premolar	Mn	DE	Pulpal necrosis	Chronic apical abscess	(+)	Unknown	(-)	0Y8M
23	Coronal	11Y10M	Female	Premolar	Mn	DE	Pulpal necrosis	Symptomatic apical periodontitis	(+)	(-)	(+)	1Y8M
24	Apical	9Y5M	Female	Incisor	Mx	Trauma	Previously initiated therapy	Symptomatic apical periodontitis	Failed	Unknown	(-)	0Y6M
25	Apical	9Y5M	Male	Incisor	Mx	Trauma	Pulpal necrosis	Symptomatic apical periodontitis	Unknown	Unknown	(+)	0Y11M
26	Coronal	12Y1M	Female	Premolar	Mn	DE	Pulpal necrosis	Symptomatic apical periodontitis	(+)	Unknown	(+)	0Y7M
27	Apical	12Y0M	Male	Premolar	Mn	DE	Pulpal necrosis	Acute apical abscess	(+)	(-)	(-)	0Y9M
28	Apical	9Y7M	Female	Incisor	Mx	Trauma	Pulpal necrosis	Chronic apical abscess	Failed	Unknown	(-)	1Y6M

29	Apical	10Y11M	Female	Premolar	Mn	DE	Previously initiated therapy	Symptomatic apical periodontitis	(+)	Unknown	(-)	0Y8M

DE, fracture of dens evaginatus; *Mx*, maxilla; *Mn*, mandible.

Table 4. Summary of radiographic findings of 33 roots

Case No.	Groups	Apical diameter decrease ratio (%)	Root length increase ratio (%)	RRA increase ratio (%)		PAR decrease ratio (%)	Root development stages		Follow-up period
				Flake *et al*., 2014[16]	Modified method		preop	postop	
1	Coronal	80.8	9.7	34.5	39.1	36.5	4	5	1Y3M
2	Coronal	56.9	0.0	6.8	22.9	97.5	3	3	1Y2M
3	Apical	49.1	18.8	55.6	83.4	96.6	3	4	1Y10M
4	Coronal	36.9	4.9	7.0	14.6	89.1	4	4	1Y10M
5	Coronal	30.3	0.2	-0.2	3.6	97.8	4	5	1Y8M
6	Coronal	65.1	5.2	2.3	20.3	73.4	4	5	1Y7M
7	Apical	54.4	-5.0	16.2	10.3	98.5	3	4	1Y1M
8	Coronal	81.0	4.0	3.4	14.3	88.9	4	5	1Y9M
9	Coronal	63.6	6.2	11.7	25.4	96.9	4	5	1Y11M

10	Apical	75.5	0.2	11.0	27.0	66.9	3	3	0Y10M
11	Coronal	85.1	17.9	21.2	51.7	96.2	3	5	1Y4M
12	Apical	37.8	7.9	22.2	94.2	98.6	3	5	1Y1M
13	Apical	91.9 57.4 72.2	18.4 4.4 8.2	3.2 3.7 2.6	49.0 55.7 43.7	88.1 83.9 61.9	4 4 4	5 5 4	1Y11M
14	Coronal	63.3	-4.4	5.5	21.7	98.6	4	5	1Y11M
15	Apical	30.9	16.7	26.7	39.1	95.1	4	5	0Y5M
16	Apical	72.3	4.3	4.3	47.0	77.4	4	5	1Y11M
17	Apical	56.0	10.8	25.6	55.9	86.3	4	5	1Y7M
18	Apical	82.0	2.0	0.3	52.8	96.8	4	5	1Y2M
19	Coronal	10.1	7.0	17.6	39.5	97.6	3	3	1Y1M
20	Apical	12.1 49.4 30.2	2.6	0.4 0.2 -4.0	10.1 21.8 18.1	86.3 77.8 80.2	4 4 4	5 5 5	1Y0M
21	Apical	47.6	-2.3	-8.7	4.9	96.4	4	5	0Y11M

22	Coronal	15.6	2.4	3.2	10.2	79.6	3	3	0Y8M
23	Coronal	89.4	7.1	25.8	26.4	97.4	4	5	1Y8M
24	Apical	24.8	-7.7	-2.8	17.3	69.1	4	5	0Y6M
25	Apical	42.0	6.1	4.1	36.3	87.4	3	3	0Y11M
26	Coronal	48.1	27.9	35.4	25.2	85.7	4	5	0Y7M
27	Apical	35.1	0.0	1.9	14.0	98.8	4	5	0Y9M
28	Apical	45.4	1.4	2.6	59.3	95.5	4	5	1Y6M
29	Apical	57.6	6.7	8.5	21.0	80.1	4	5	0Y8M

RRA, radiographic root area; *PAR*, periapical rarefaction

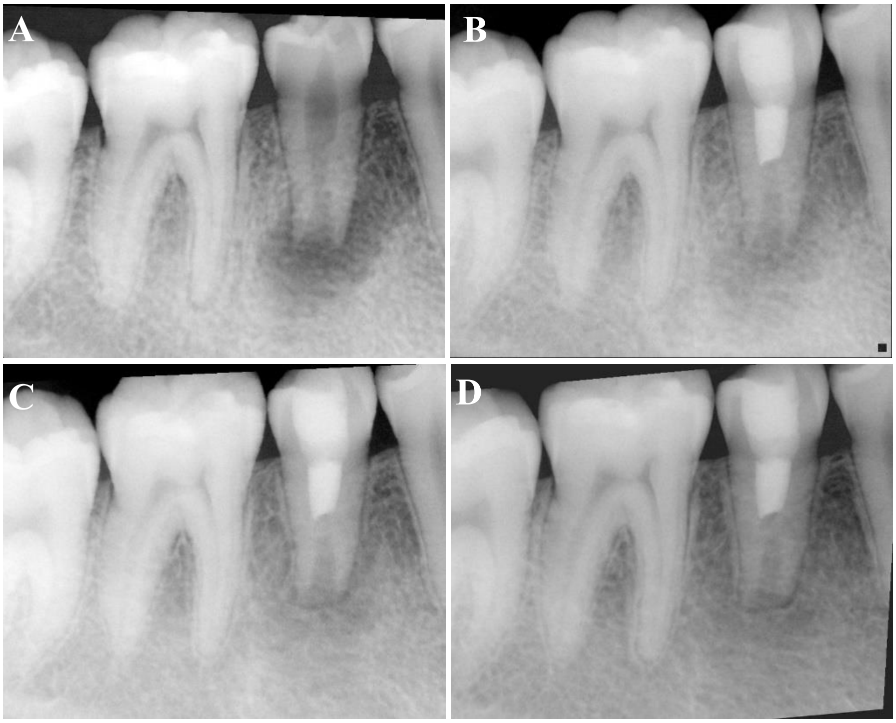

Figure 1. A series of periapical radiographs standardized using TurboReg plugin: (A) preoperative, (B) postoperative, (C) 8 months follow-up, (D) 14 months follow-up.

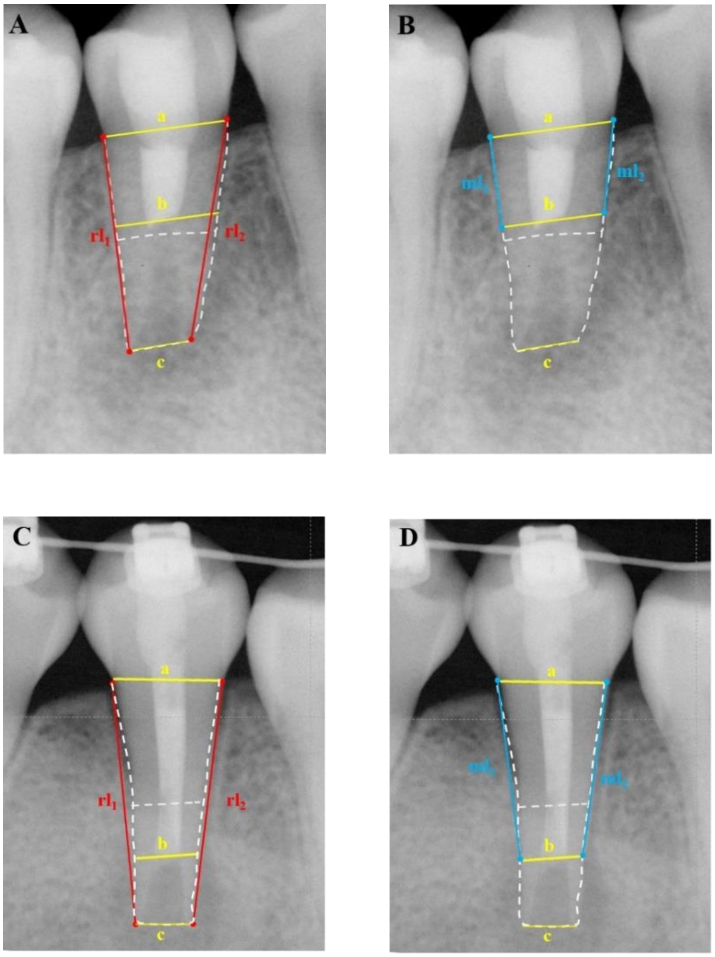

Figure 2. Determination of the location of apical border of MTA plug. White dotted line depicts root outline and imaginary mid-root portion. a (yellow), a line connecting the mesial and distal cementoenamel junction (CEJ); b (yellow), a line depicting apical border of the MTA plug extended to outer root surface. c (yellow), apical border. The apical border location data of MTA plug were calculated as the percentage ratio of the average length of mesial (ml1) and distal(ml2) circumscriptions from CEJ to total root length (average of rl1 and rl2). Representative diagrams of teeth in coronal (A, B) and apical (C, D) group. *MTA*, mineral trioxide aggregate.

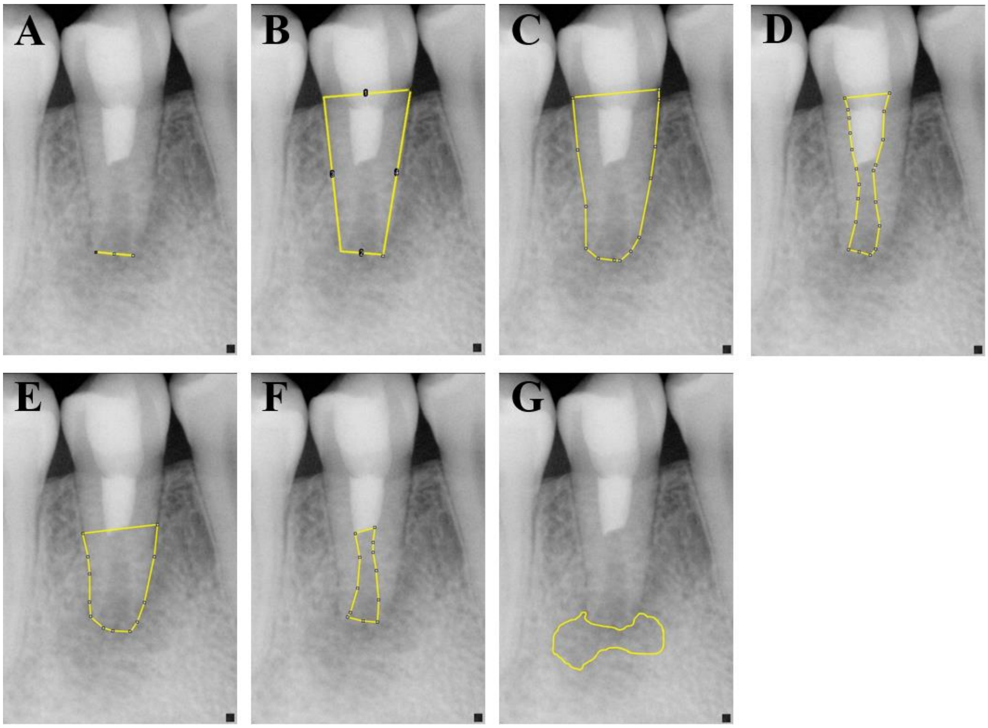

Figure 3. Digital measurements of four radiographic changes: (A) apical diameter, (B) root length, (C, D) RRA according to Flake *et al*. [16], (E, F) modified RRA, (G) periapical rarefaction area. *RRA,* radiographic root area.

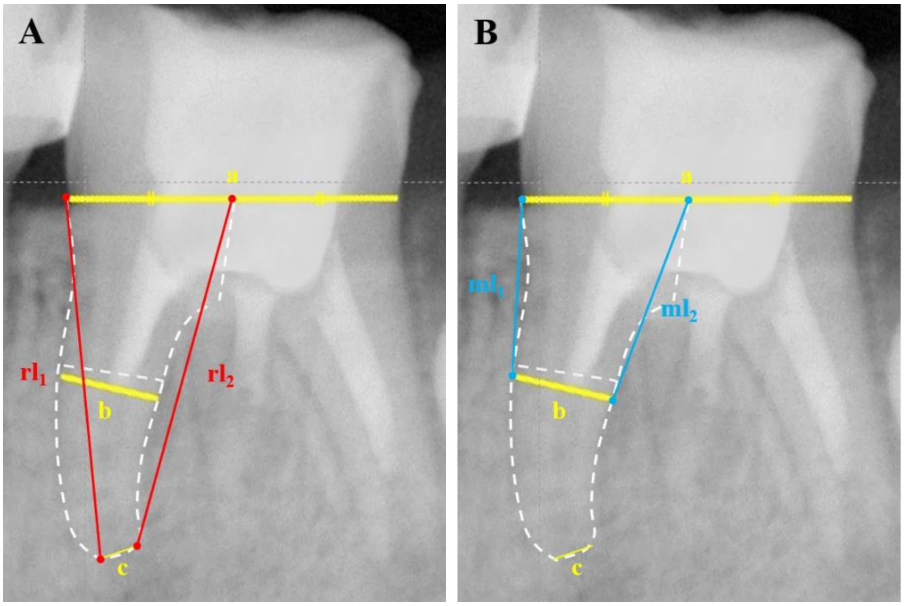

Figure 4. Determination of the location of apical border of MTA plug in multirooted tooth. A line was drawn from the center of furcation to the midpoint of a line connecting the mesial and distal CEJ. This line served as the mesial or distal limit of each root, which allowed each root to be assessed separately. *MTA*, mineral trioxide aggregate; *CEJ*, cementoenamel junction.

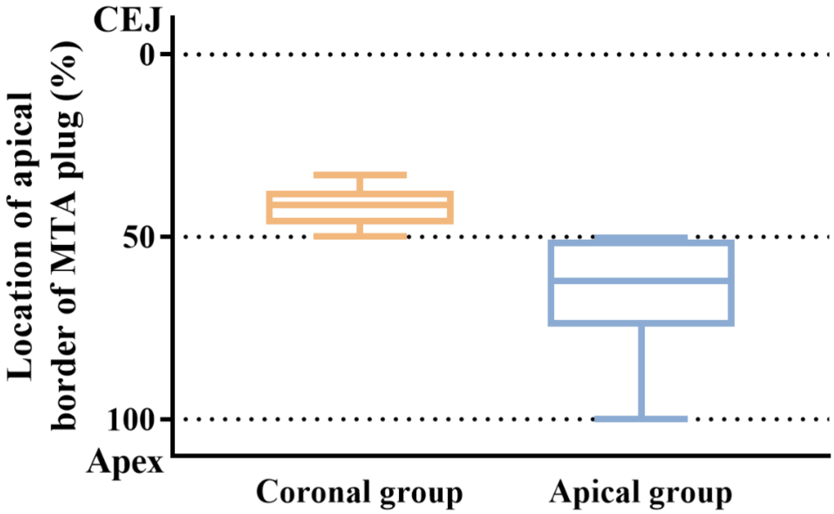

Figure 5. The location of apical border of MTA plug. Its relative location in root canal was expressed as a percentage, as described in Figure 2. *MTA*, mineral trioxide aggregate.

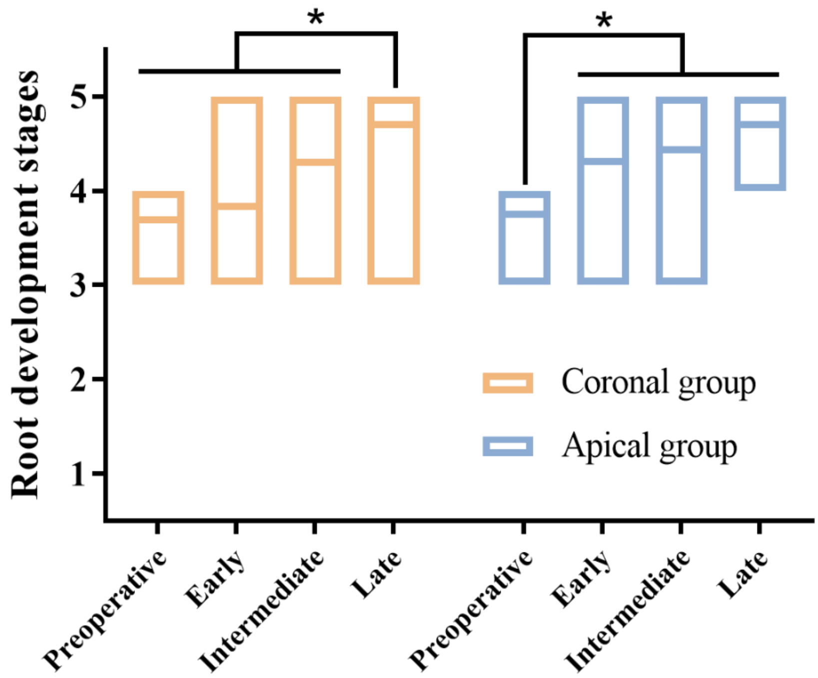

Figure 6. Root development stages in coronal and apical groups. Significant changes in root development stages occurred at the late period in coronal group, and at the early period in apical group. Asterisks indicate statistically significant differences among the groups ($P < 0.05$).

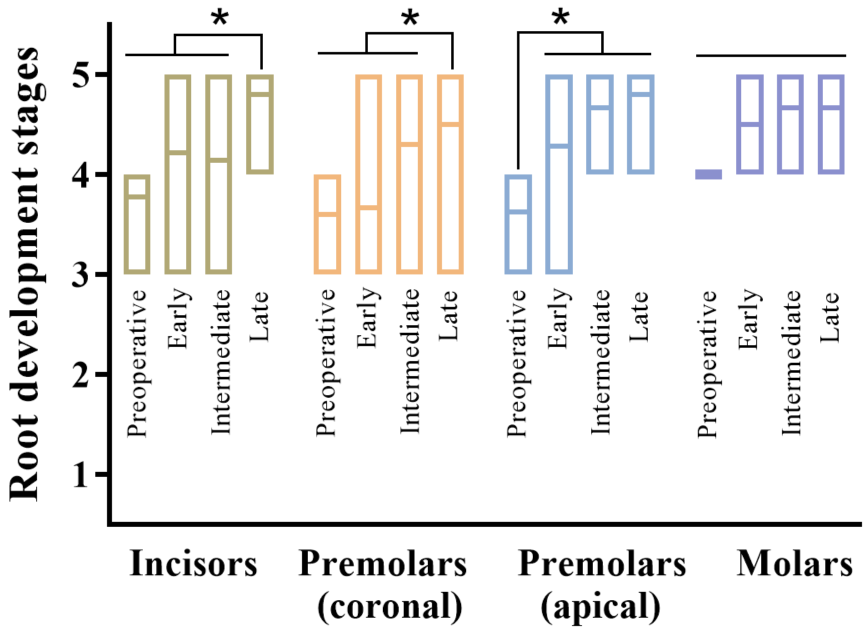

Figure 7. Changes in root development stages after regenerative endodontic procedures in each tooth type. Regardless of groups, incisors showed significant change in root development stage at late period ($P < 0.05$) and molars did not exhibit any changes in root development stage throughout the entire follow-up ($P > 0.05$). Premolars in coronal and apical groups showed significant change of root development stages at different periods ($P < 0.05$). Asterisks indicate statistically significant differences among the groups ($P < 0.05$). *MTA*, mineral trioxide aggregate.

국문초록

재생근관치료 시 MTA plug 하연의 위치가 치근 발달에 미치는 영향에 대한 후향적 연구

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1. 목적

본 연구는 괴사 치수 및 치근단 치주염을 가지는 미성숙 영구치에 시행한 재생근관치료에서, 근관 내 mineral trioxide aggregate (MTA) plug 하연의 상대적인 위치가 치근 발달에 미치는 영향을 후향적으로 조사하였다. 귀무가설은 다음과 같다: 근관 내 MTA plug 하연의 위치가 치근단 치주염을 동반하거나 동반하지 않는 괴사 치수를 가지는 미성숙 영구치의 재생근관치료 후 치근

발달에 영향을 미치지 않는다.

2. 재료 및 방법

서울대학교치과병원 치과보존과에서 2012년 3월 14일부터 2019년 2월 18일까지 재생근관치료가 시행된 환자들의 임상적, 방사선학적 기록을 수집하였다. 29명의 환자의 33개의 치근에 대해 미국근관치료학회의 지침을 따르는 재생근관치료가 시행되었다. 방사선학적 치근단공의 직경, 치근과 근관의 면적, 그리고 치근단 투과상 크기의 변화를 방사선학적으로 평가하였다. 치근단 방사선 사진을 바탕으로, 전체 치근 길이에 대한 MTA plug 하연의 위치를 기준으로 각 치근들을 두 그룹으로 나누었다. 치근 길이의 치관부 1/2에 MTA plug 하연이 위치하는 치근들을 coronal 그룹 (n = 13), 근단부 1/2에 위치하는 치근들을 apical 그룹 (n = 20)으로 지정하였다. 치료 전, 후를 포함하는 일련의 치근단 방사선 사진들을 ImageJ software와 TurboReg plugin을 이용하여 표준화하였다. 이를 바탕으로 치근단공의 직경, 치근의 길이, radiographic root area (RRA), modified RRA (mRRA), 그리고 치근단 투과상의 크기를 측정하였고 치근 발달 단계를 평가하였다.

3. 결과

29명의 환자로 구성된 모집단의 평균 연령은 11세 10개월이었다. 두 그룹간 나이, 성별, 치아의 종류, 악궁의 위치 (상악 혹은 하악) 및 치료 전 치근 발달 단계의 통계적 유의차는 존재하지 않았다 ($P > 0.05$). 치아의 종류는 소구치가 가장 많았으며 (62.1%), 그 다음으로 전치 (31.0%), 대구치 (6.9%) 순이었다. 모든 증례에서 치료 전과 비교하여 유의한 수준의 치근단공 직경 감소, 치근단 투과상의 소실이 관찰되었고, 치근 길이, RRA, mRRA의 증가가 관찰되었다. 그러나 mRRA 증가율은 apical 그룹에서 초기 (3 - 6개월)와 후기 (13 - 24개월) 에서 coronal 그룹에 비해 유의하게 높은 값을 보였다 ($P < 0.05$). 더불어, coronal 그룹에서는 유의할 만한 치근단 성숙이 후기에 관찰된 반면, apical 그룹은 초기에 관찰되었다 ($P < 0.05$).

4. 결론

본 연구에서 MTA plug의 하연의 위치는 재생근관치료 후 치근 발달에 유의한 영향을 미치지 않았다. 24 개월 이내의 경과 관찰에서, mRRA 증가율과 치근 발달 단계에서 두 그룹 간 유의차가 관찰되었다.

주요어 : 미성숙영구치, mineral trioxide aggregate plug의 위치, radiographic root area, 재생근관치료, 치근발달단계

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