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Original Article

Outcomes of necrotic immature open-apex central incisors treated by MTA apexification using poly(ε-caprolactone) fiber mesh as an apical barrier

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poly(ε-caprolactone) fiber mesh

Background/purpose: Although unset mineral trioxide aggregate (MTA) has some cytotoxicity, MTA is still a biocompatible material suitable for doing apexification. This study assessed the outcomes for 8 necrotic immature open-apex permanent maxillary central incisors treated by MTA apexification using poly(ε-caprolactone) fiber mesh (PCL-FM) as an apical barrier (so-called PCL-FM/MTA apexification) to prevent extrusion of MTA materials into the periapical tissues of open-apex teeth.

Methods: Eight necrotic immature open-apex permanent maxillary central incisors with the open apices measuring 2.5 mm–3.5 mm in diameter in 8 patients (6 boys and 2 girls; age range, 8–10 years) were first cleaned using ultrasonic activated irrigation with 2.5% sodium hypochlorite solution and then treated by PCL-FM/MTA apexification procedure.

Results: All the 8 permanent maxillary central incisors showed successful outcomes after PCL-FM/MTA apexification procedure. The mean duration for apical hard tissue barrier formation of the 8 incisors was 6.8 ± 0.5 weeks (range 6–7 weeks). The mean increased root length was 1.8 ± 0.7 mm (range 1–3 mm) at 7 weeks and 3.1 ± 0.6 mm (range 2–4 mm) at 3 months.

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The mean increased dentinal wall thickness at the most apical portion of the root was 1.3 ± 0.5 mm (range 1–2 mm) at 7 weeks and 2.4 ± 0.6 mm (range 1.5–3 mm) at 3 months. None of the teeth treated by PCL-FM/MTA apexification showed tooth discoloration after a follow-up period of 3 months.
Conclusion: PCL-FM/MTA apexification is an excellent technique for treatment of necrotic immature open-apex permanent maxillary central incisors.

Introduction

Traffic and sports/recreational accidents occur frequently in children between 7 and 10 years of age and account for 30% of the patients suffering from traumatic injuries of teeth.[1] During the trauma incident, maxillary and mandibular incisors are commonly injured. This trauma event usually results in pulp necrosis of immature permanent incisors in children of 7–10 years of age.[2] A prolonged treatment period may increase the risk of infection. It is rather difficult to prepare or debride open-apex incisors without damaging the thin-brittle dentinal wall for performing the apexification procedure. Moreover, excessive hand filing may damage remnants of Hertwig's root sheath and the apical papilla,[3] stopping further root apex formation. In addition, excessive hand filing may further weaken the immature permanent teeth with thin dentinal wall, resulting in fracture of teeth after treatment. Ultrasonic filing has a high potential to replace the conventional hand filing, because it has a high efficacy on cleaning the infected root canal.[4–6] If combined with an antibacterial irrigating solution, ultrasonics may promote rapid penetration of antimicrobial agents into the dentinal tubules, subsequently producing a sonosynergisitic effect to disinfect the root canal system.[5] A small file used ultrasonically without direct contact with the root canal wall can create greater acoustic streaming, higher velocity, more power and better efficiency to clean the root canal surface than a large file in direct contact with the root canal wall.[6] The resultant preservation of root structure helps to prevent the fracture of thin-walled necrotic immature permanent teeth treated with calcium hydroxide apexogenesis.[2]

Mineral trioxide aggregate (MTA) can promote the differentiation of dental pulp cells into odontoblast-like cells that are needed for apexogenesis procedure and finally resulting in successful clinical outcomes in a short period of time.[7,8] Even though MTA is biocompatible and has been popularly utilized in apexification procedure, cytotoxicity of MTA is revealed resulting in cell death after 1 h of MTA hydration in MDPC 23 cell cultures.[9] Moreover, MTA extruded from the opened apical foramen to the periapical tissue may induce tissue toxicity and delay healing. Another disadvantage of MTA is the grey discoloration of the tooth when the MTA is placed in the crown and cervical area of the tooth.[10–12] These complications can be avoided by enveloping the MTA with some kinds of fiber mesh that can preserve the original function of MTA but eliminate the side effect of MTA. A nanofiber, electronspun poly(ε-caprolactone) fiber (PCL-F) has been approved by FDA and widely used as a scaffold for tissue engineering in orthopedics, dermatology, hematology, and neurology for more than 10 years.[13–19] Our previous study showed PCL-F mesh (PCL-FM) combined with MTA is a better combination material than MTA alone for direct pulp capping of human permanent teeth.[20]

This study reported the outcomes for 8 necrotic immature open-apex permanent maxillary central incisors that were firstly cleaned by ultrasonic activated irrigation with 2.5% sodium hypochlorite solution, and then treated by MTA apexification using PCL-FM as an apical barrier (so-called PCL-FM/MTA apexification) to prevent extrusion of MTA materials into the periapical tissues of the open-apex teeth. The apical hard tissue barrier formation, increased root length, increased dentinal wall thickness at the most apical portion (perhaps 1.5–3 mm) of the root, post-operation symptoms, signs, and tooth discoloration were observed after PCL-FM/MTA apexification procedure. The main purpose of this prospective case series study was to evaluate the outcomes of necrotic immature open-apex permanent maxillary central incisors after treatment with PCL-FM/MTA apexification.

Materials and methods

Eight necrotic immature permanent maxillary central incisors with open apices measuring 2.5–3.5 mm in diameter were included in this study. They were from 8 patients (6 boys and 2 girls; mean age, 9.4 ± 0.7 years; age range, 8–10 years) who were treated in the Department of Dentistry, Taipei City Hospital, Renai Branch, Taipei, Taiwan. The 8 maxillary central incisors included 3 right and 5 left central incisors (Table 1). All the 8 incisors were diagnosed as having pulp necrosis by the cold test and electric pulp test. The most common reason causing pulp necrosis was motor vehicle accident (3 teeth), followed by accidental fall (2 teeth), sports injury (2 teeth), and playground injury (one tooth). The symptoms and signs of 8 patients with the necrotic immature incisors included pain (8 teeth), crown fracture (3 teeth), fever (2 patients), swelling (one tooth), and gingival redness (one tooth). All the 8 necrotic maxillary central incisors had periapical radiolucent lesions. Moreover, the clinical photographs and radiographs of the first four cases are shown in Figs. 1–4. This study was approved by the Institutional Review Board of Taipei City Hospital, Renai branch, Taipei, Taiwan.

All the 8 maxillary central incisors were treated by PCL-FM/MTA apexification procedure. In brief, the pulp

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Table 1 Clinical and radiographic information for 8 patients with 8 necrotic immature open-apex maxillary central incisors treated by MTA apexification using poly(ε-caprolactone) fiber mesh (PCL-FM) as an apical barrier.

Age (year)	Sex	Tooth number	Reason of pulp necrosis	Clinical symptoms and signs	Time for apical barrier formation (week)	Increased root length (mm)		Increased dentinal wall thickness at the most apical portion of the root (mm)	
						7 weeks	3 months	7 weeks	3 months
10	M	11	Motor vehicle accident	Swelling, redness, pain, fever	7	2	3	1	2
8	M	11	Accidental fall	Mild pain, crown fracture	7	1	3	1	3
9	M	21	Playground injury	Pain, crown fracture, fever	7	2	4	2	3
9	M	11	Accidental fall	Mild pain	7	2	3	1	1.5
10	M	21	Motor vehicle accident	Mild pain	6	1	3	1	3
10	F	21	Motor vehicle accident	Mild pain	6	3	4	1	2
9	F	21	Sports injury	Mild pain	7	2	3	1	2
10	M	21	Sports injury	Pain, crown fracture	7	1	2	2	3

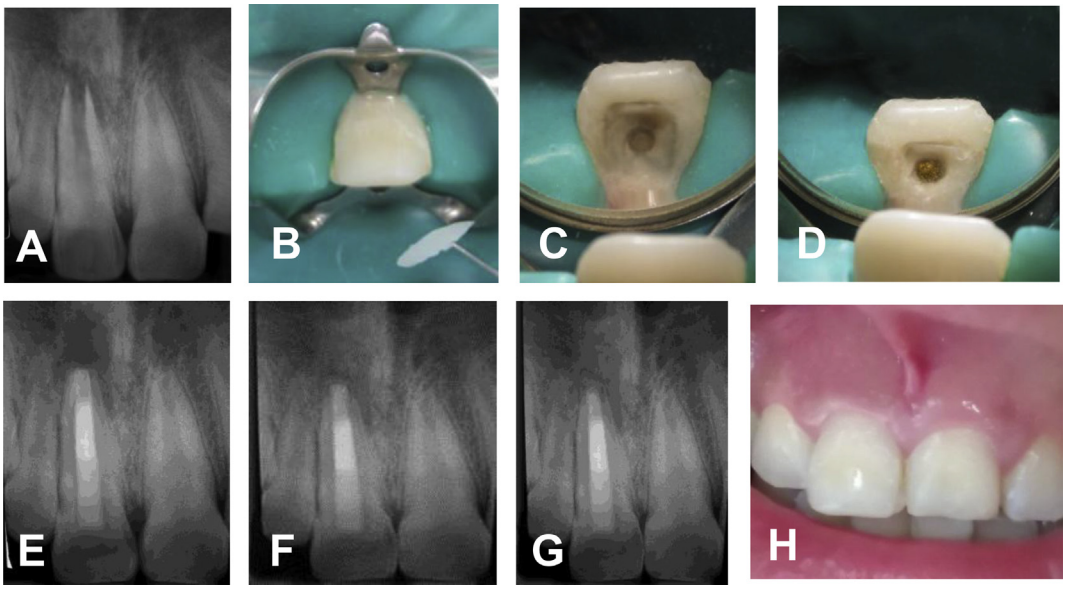

Fig. 1 Case 1 of Table 1. (A) The initial periapical radiograph of the open-apex right maxillary central incisor with a periapical radiolucent lesion. (B) The isolated right maxillary central incisor and a piece of 7 × 7 mm and 0.5-mm-thick PCL-FM carried at the tip of a size-35 spreader. (C) The exactly-placed PCL-FM at its final position where is 1 mm shorter than the end of the open root apex. (D) The treated tooth after the placement of 5-mm-long MTA cylinder in the apical third of the root canal. (E) Periapical radiograph showing the filling of the root canal with the MTA at the apical third, the gutter-percha points at the middle third, and the dentin-bonding light-curing composite resin at the coronal third immediately after treatment. (F) The partial healing of the periapical radiolucent lesion 7 weeks after treatment. (G) The complete healing of the periapical radiolucent lesion, increased root length, and increased thickness of dentinal wall at the most apical 2-mm portion of the root 3 months after treatment. (H) The treated right maxillary central incisor with healthy gingiva and no discoloration 3 months after treatment.

chamber was accessed, the canal pathway was found by the size 10 or 15 hand K file, and the working length which was 1 mm shorter than the apical end of the open apex was established. The ultrasonic activated irrigation was performed with the ENAC ultrasonic machine (OE-2, 30 kHz, OSADA Electric Co., Ltd., Tokyo, Japan) for root canal debridement, and 2.5% sodium hypochlorite solution was used during or after the ultrasonic activated irrigation of the root canal. For easy management, the maxillary arch of the patient was positioned horizontally before the

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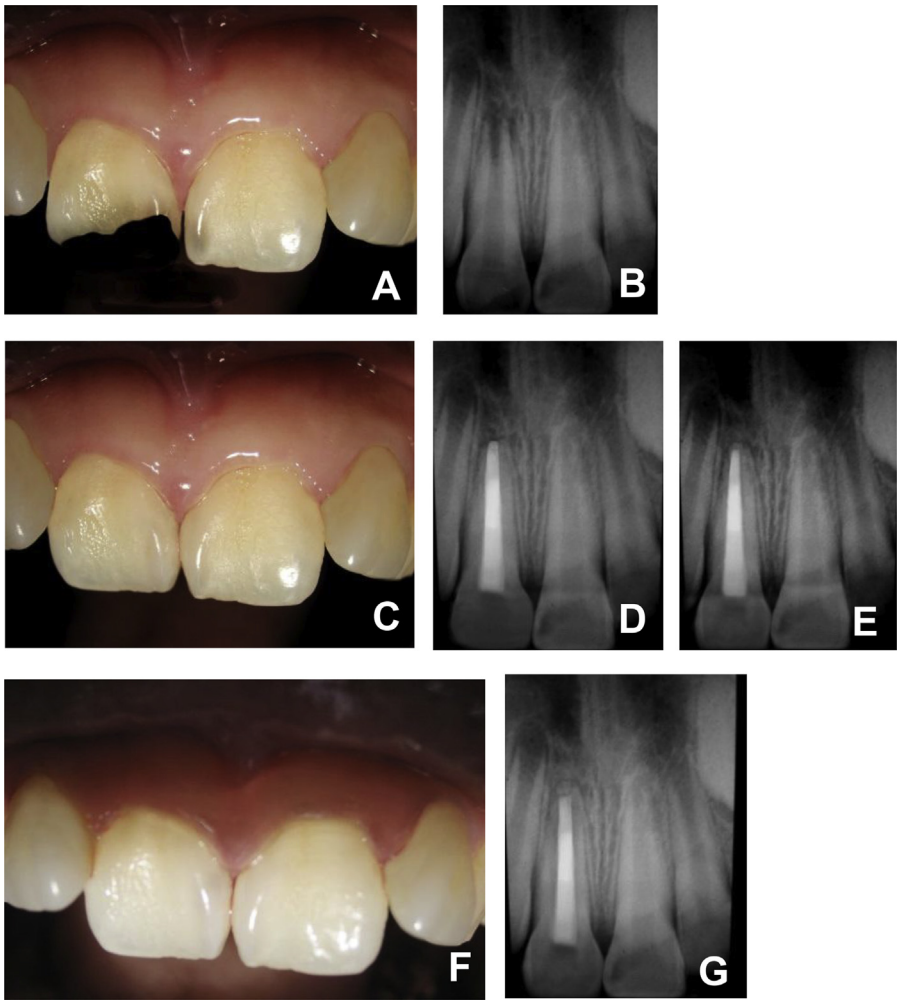

Fig. 2 Case 2 of Table 1. (A) The right maxillary central incisor with the enamel-dentin crown fracture. (B) The initial periapical radiograph of the open-apex right maxillary central incisor with a periapical radiolucent lesion. (C) The filling of the fractured crown with dentin-bonding light-curing composite resin. (D) Periapical radiograph showing the filling of the root canal with the MTA at the apical third, the gutter-percha points at the middle third, and the dentin-bonding light-curing composite resin at the coronal third immediately after treatment. (E) The partial healing of the periapical radiolucent lesion 7 weeks after treatment. (F) The treated right maxillary central incisor with healthy gingiva and no discoloration 3 months after treatment. (G) The complete healing of the periapical radiolucent lesion, increased root length, and increased thickness of dentinal wall at the most apical 3-mm portion of the root 3 months after treatment.

ultrasonic activated irrigation. In the entire ultrasonic activated irrigation procedure, the root canal was pre-filled with the 2.5% sodium hypochlorite solution and the working file was kept in a position without contacting the root canal wall to increase the cleaning efficacy and to prevent from damaging the thin dentinal wall of the root. A size-15 file was inserted into the root canal up to 1—2 mm shorter than the working length, maintained in a fixed position, and kept oscillating for 10 s. Then, it was moved up and down and kept oscillating for another 60 s. After that, the size-30 file was inserted into the root canal without contacting the root canal wall and kept oscillating for another 90 s using 2.5% sodium hypochlorite solution. A size-15 file was used again and kept oscillating for another 20 s. Thus, the rate for root canal irrigation was 30 ml of 2.5% sodium hypochlorite solution per minute and the total amount of irrigation solution used was 90 ml.

After finishing the ultrasonic activated irrigation procedures, the root canal was dried by paper points and loosely packed with calcium hydroxide in the coronal root canal as an intracanal medicament for 7 days. The access cavity was sealed with Caviton (GC, Aichi, Japan). Because all of our patients had a periapical lesion with chronic inflammatory and some grade of acute exacerbation due to bacterial infection, augmentin (amoxicillin 875 mg and clavulanic acid 125 mg, oral administration, one tablet per day for 5 days) or unasyn (ampicillin and sulbactam 375 mg, oral administration, one tablet per day for 5 days) was prescribed to all patients to overcome the bacterial infection.

During the second visit, the root canal was repeatedly irrigated with 2.5% sodium hypochlorite solution and then dried by the number-35 paper points. For performing the PCL-FM/MTA apexification, a piece of 7 $\times$ 7 mm and 0.5-

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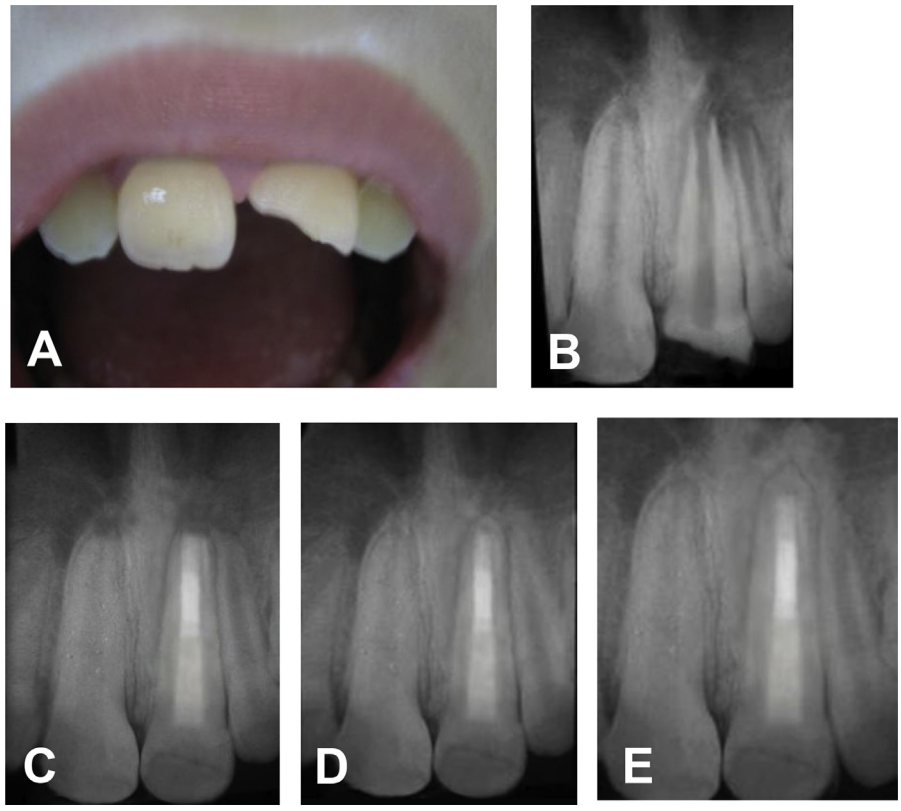

Fig. 3 Case 3 of Table 1. (A) The left maxillary central incisor with the enamel-dentin crown fracture. (B) The initial periapical radiograph of the open-apex left maxillary central incisor with a periapical radiolucent lesion. (C) Periapical radiograph showing the filling of the root canal with the MTA at the apical third, the gutter-percha points at the middle third, and the dentin-bonding light-curing composite resin at the coronal third immediately after treatment. (D) The partial healing of the periapical radiolucent lesion 7 weeks after treatment. (E) The complete healing of the periapical radiolucent lesion, increased root length, and increased thickness of dentinal wall at the most apical 3-mm portion of the root 3 months after treatment.

mm-thick PCL-FM was carried at the tip of a size-35 spreader with the working length being marked and pushed into the root canal to 1 mm shorter than the open apical end (Fig. 1B and C). If the first piece of the PCL-FM was broken or there was a suspicion of displacement of the PCL-FM, the second piece of PCL-FM of the same size was placed onto the first one till 1 mm shorter than the open apical end. Then, a 1.5-mm-thick layer of MTA (ProRoot MTA; Dentsply Tulsa Dental Specialties, York, PA, USA) paste that was mixed with a powder to water ratio of 3: 1 (v/v) was applied onto the properly-placed PCL-FM and gently compacted with a root canal plugger. The MTA paste was applied again and condensed to form a final 3- to 5-mm layer of cement barrier to separate the root canal system from the periapical tissue (Fig. 1D). A wet cotton pellet was placed against the unset MTA and the coronal cavity was sealed with IRM (Caulk, Dentsply, Milford, DE, USA). After 6 h or the next day, the IRM and cotton pellet were removed to check whether the MTA was completely enveloped by the PCL-FM, whether there was displacement of PCL-FM/MTA, and whether the filled MTA had completely set and hardened. If the MTA did not set properly, the same procedure was repeated until the filled MTA had properly placed and set.

After the filled MTA had properly placed and set, the root canals were filled with gutta-percha points (DiaDen, Almere, Netherlands) and root canal sealer (Canals, Showa, Tokyo, Japan) using the lateral condensation technique. The coronal cavity was restored with dentin-bonding light-curing composite resin (Shofu Inc., Tokyo, Japan). Periapical radiography was performed immediately after the PCL-FM/MTA apexification procedure (Fig. 1E). Most of the cleaning and filling procedures for the treated teeth were carried out without using the surgical operating microscope, but the dental microscope (Spectra 300 dental microscope, Miller Electric Manufacturing Co., Appleton, WI, USA) was used to check whether the critical procedures were performed properly.

The patient was followed up once per week in the first 7 weeks and once per two weeks from the eighth week to 3 months. At each visit, the treated tooth was checked by periapical radiography to examine the radiodensity of the most apical portion of the root and whether there were formation of an apical hard tissue barrier and continuous apical root development with increased root length and increased thickness of dentinal wall at the most apical portion of the root (Fig. 1F and G). Moreover, clinical photograph of the treated tooth was taken to evaluate the gingival condition and whether there was tooth discoloration (Fig. 1H). In this study, the time from the initial therapy to the apical hard tissue barrier formation was recorded. The root length was measured from

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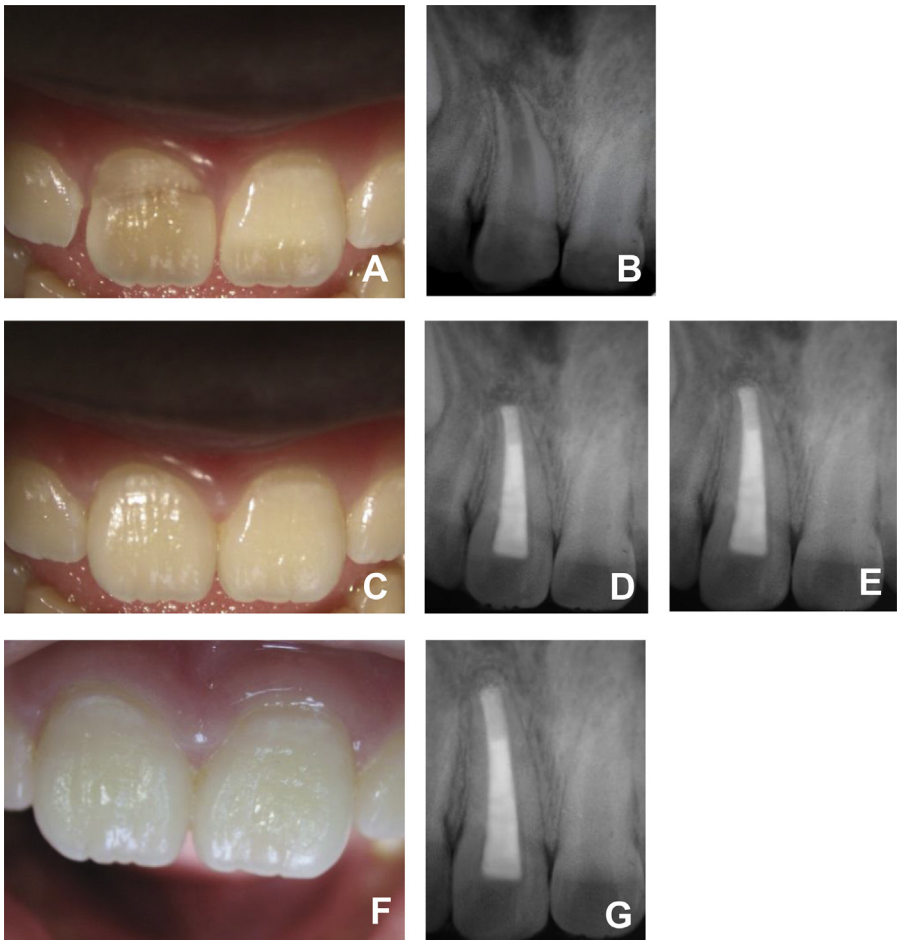

Fig. 4 Case 4 of Table 1. (A) The right maxillary central incisor with a mesio-distal fracture line at the cervical third of the crown. (B) The preoperative periapical radiograph of the open-apex and curved right maxillary central incisor with a mesio-distal fracture line at the cervical third of the crown and a periapical radiolucent lesion. (C) The bonding of the fractured crown with dentin-bonding light-curing composite resin. (D) Periapical radiograph showing the filling of the root canal with the MTA at the apical third, the gutter-percha points at the middle third, and the dentin-bonding light-curing composite resin at the coronal third immediately after treatment. (E) The partial healing of the periapical radiolucent lesion 7 weeks after treatment. (F) The treated right maxillary central incisor with healthy gingiva and no discoloration 3 months after treatment. (G) The complete healing of the periapical radiolucent lesion, increased root length, and increased thickness of dentinal wall at the most apical 1.5-mm portion of the root 3 months after treatment.

cementoenamel junction to the apical root end, and the dentinal wall thickness at the most apical portion of the root was measured at baseline, at 7 weeks, and at 3 months.

Results

The mean time for apical hard tissue barrier formation of the 8 incisors was 6.8 $\pm$ 0.5 weeks (range 6—7 weeks). The mean increased root length was 1.8 $\pm$ 0.7 mm (range 1—3 mm) at 7 weeks and 3.1 $\pm$ 0.6 mm (range 2—4 mm) at 3 months. The mean increased dentinal wall thickness at the most apical portion of the root was 1.3 $\pm$ 0.5 mm (range 1—2 mm) at 7 weeks and 2.4 $\pm$ 0.6 mm (range 1.5—3 mm) at 3 months (Table 1). None of the teeth treated by PCL-FM/MTA apexification showed tooth discoloration after a follow-up period of 3 months. Moreover, all the 8 necrotic immature open-apex maxillary central incisors had the apical radiolucent lesions which showed complete healing 3 months after treatment with PCL-FM/MTA apexification. Therefore, all the 8 treated incisors demonstrated excellent outcomes 3 months after PCL-FM/MTA apexification procedure. The clinical photographs and radiographs of the first four cases are shown in Figs. 1—4.

Discussion

In this study, 8 necrotic immature open-apex permanent maxillary central incisors were mainly treated by ultrasonic activated irrigation with 2.5% sodium hypochlorite solution and PCL-FM/MTA apexification procedure. After an observation period of 3 months, we found that all symptoms and signs associated with the diseased teeth disappeared, all the periapical radiolucent lesions revealed complete regression, all the treated teeth showed formation of apical hard tissue barrier, completion of apical root development

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with increased root length and increased thickness of the dentinal wall at the most apical portion of the root, and no tooth discoloration after treatment. These findings indicate that our PCL-FM/MTA apexification procedure is an excellent technique for treatment of necrotic immature open-apex permanent maxillary central incisors.

The disappearance of symptoms and signs as well as the healing of periapical radiolucent lesions were mainly due to the effective disinfection of the root canal system by our treatment procedures. In this study, all the diseased teeth were treated by ultrasonic activated irrigation with 2.5% sodium hypochlorite solution. The 2.5% sodium hypochlorite solution is an excellent agent that can dissolve pulp tissue; it also possesses a broad-spectrum antimicrobial activity against biofilms and endodontic microorganisms including enterococci, actinomyces, and candida organisms that are difficult to eradicate from the root canals.[21–24] In addition, ultrasonic machines can provide both energized filing and continuous irrigation with a large volume of disinfected solution simultaneously. Ultrasonic activated irrigation alone can rupture the bacterial cell wall and provide an effective cleaning of the infected root canal system including the infected dentinal tubules.[5,6,25] If combined with an antibacterial irrigating solution, ultrasonics may promote rapid penetration of antimicrobial agents into the dentinal tubules, subsequently producing a sonosynergisitic effect to disinfect the root canal system.[5] A small file used ultrasonically without direct contact with the root canal wall can create greater acoustic streaming, higher velocity, more power and better efficiency to clean the root canal surface than a large file in direct contact with the root canal wall.[6] The resultant preservation of root structure helps to prevent the fracture of thin-walled necrotic immature permanent teeth treated with calcium hydroxide apexogenesis.[2] The aforementioned findings indicate that ultrasonic activated irrigation with 2.5% sodium hypochlorite solution using a small file do provide effective disinfection of the root canal system, finally resulting in disappearance of symptoms and signs as well as the healing of periapical radiolucent lesions.

Our PCL-FM/MTA apexification procedure for necrotic immature permanent maxillary central incisors is a kind of regenerative endodontic treatment that results in continued apical root development, increased thickness of the dentinal wall at the most apical portion of the root, and apical closure. The advantages of using PCL-FM/MTA apexification procedure for treatment of immature open-apex permanent incisors were described as follows. First, PCL-FM can be used as a physical barrier to prevent the cytotoxicity of unset MTA,[26] and the extrusion of MTA materials into the periapical tissues of open-apex teeth, resulting in a prompt healing of the periapical lesion. A previous study also showed that PCL-FM can segregate MDPC23 cells from the noxious effect of unset MTA and reduce cell death to 8% of that in the MTA alone group.[9] Second, the placement of MTA in the apical root canal forms a hermetic sealing to segregate the residual microorganisms and their toxic products from diffusion into the periapical tissue.[10] Moreover, MTA can promote pulp cell survival and proliferation; up-regulate the expression of transcription factors and genes like those of osteopontin, alkaline phosphatase, runt-related transcription factor 2, and dentin sialoprotein; promote the differentiation of dental pulp cells into odontoblast-like cells; and induce dentin bridge formation and regeneration of a healthy dentin-pulp complex.[7,27–32] Third, PCL-FM/MTA can also promote the differentiation of mesenchymal stem cells from residual viable pulp or apical papilla into odontoblast-like cells that in turn form the apical hard tissue barrier and complete the apical root development with increased root length and increased thickness of dentinal wall at the most apical portion of the root. A previous study also demonstrated that PCL-FM/MTA can promote the differentiation of MDPC23 cells into odontoblast-like cells and biomineralization as confirmed by the expression of alkaline phosphatase and dentin sialophosphoprotein and by the deposition of calcium.[26] Our previous study showed excellent clinical outcomes for the diseased teeth treated by PCL-FM/MTA direct pulp capping.[20] Yang et al.[33] also found that dental pulp stem cells can seed onto the nanofibrous PCL/gelatin/nHA scaffold, which can up-regulate alkaline phosphatase activity and promote osteocalcin expression. The findings of the aforementioned studies including the present study may elaborate that PCL-FM/MTA can be used to establish a functional osteoid-dentin-cementum complex in the root apices of human immature permanent teeth. However, the PCL-FM/MTA apexification is an intricate procedure that may need the help of a dental microscope and a sophisticated skill to complete it.

We further explain why immature open-apex permanent incisors can have the high potential to form the apical hard tissue barrier and complete the apical root development after PCL-FM/MTA apexification procedure. Immature permanent incisors have a wide root canal and apical foramen that permits the ingrowth of small blood vessels and survival of some residual pulp tissues. Furthermore, stem cells of apical papilla may survive from the infection because of their proximity to the rich vasculature of periapical tissues.[3] The apical root development needs both epithelial cells of Hertwig's root sheath and odontoblasts. Hertwig's root sheath epithelial cells are present at the apical end of immature roots and are resistant to destruction, even in the presence of inflammation.[34] Hertwig's root sheath epithelial cells can induce the differentiation of mesenchymal stem cells from residual viable pulp or apical papilla into odontoblasts that subsequently form the apical root dentin and complete the apical root formation.[3,34] In this study, it took an average of 6.8 ± 0.5 weeks for 8 necrotic immature open-apex permanent maxillary central incisors to form the apical hard tissue barrier. Pradhan et al.[35] showed that open-apex teeth treated with hand filing plus MTA or calcium hydroxide take a mean duration of 3 ± 2.9 months or 7 ± 2.9 months to form the apical hard tissue barrier, respectively. El-Meligy and Avery[36] also demonstrated that open-apex teeth treated with hand filing plus MTA or calcium hydroxide needed approximately 12 months to form the apical hard tissue barrier. We believe that the effective disinfection of the root canal system by ultrasonic activated irrigation with 2.5% sodium hypochlorite solution and the use of PCL-FM/MTA for apexification procedure may be the major reasons that explain why the diseased immature open-apex permanent maxillary central incisors need the shorter mean time relative to other techniques for apical hard tissue barrier formation in this study.

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In this study, 8 necrotic immature open-apex permanent maxillary central incisors treated by ultrasonic activated irrigation with 2.5% sodium hypochlorite solution plus PCL-FM/MTA apexification procedure needed a relatively short mean duration for apical hard tissue barrier formation. After an observation period of 3 months, all the symptoms and signs associated with tooth pulp necrosis disappeared. Moreover, all the treated teeth showed complete healing of periapical radiolucent lesions and completion of apical root development with increased root length and increased thickness of dentinal wall at the most apical portion of the root after treatment. We conclude that PCL-FM/MTA apexification is an excellent technique for treatment of necrotic immature open-apex permanent maxillary central incisors.

Conflict of interest

The authors have no conflicts of interest relevant to this article.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.jfma.2018.06.008.

References

1. Skaare AB, Jacobsen I. Etiological factors related to dental injuries in Norwegians aged 7–18 years. *Dent Traumatol* 2003;**19**:304–8.
2. Rafter M. Apexification: a review. *Dent Traumatol* 2005;**21**:1–8.
3. Huang GTJ, Sonoyama W, Liu Y, Liu H, Wang S, Shi S. The hidden treasure in apical papilla: the potential role in pulp/dentin regeneration and bioroot engineering. *J Endod* 2008;**34**:645–51.
4. Richman MJ. The use of ultrasonics in root canal therapy and root resection. *J Dent Med* 1957;**12**:12–8.
5. Martin H. Ultrasonic disinfection of the root canal. *Oral Surg* 1976;**42**:92–9.
6. Ahmad M, Pitt Ford TR, Crum LA. Ultrasonic debridement of root canals: acoustic streaming and its possible role. *J Endod* 1987;**13**:490–5.
7. Seo MS, Hwang KG, Lee J, Kim H, Baek SH. The effect of mineral trioxide aggregate on odontogenic differentiation in dental pulp stem cells. *J Endod* 2013;**39**:242–8.
8. Jeeruphan T, Jantarat J, Yanpiset K, Suwannapan L, Khewsawai P, Hargreaves KM. Mahidol study 1: comparison of radiographic and survival outcomes of immature teeth treated with either regenerative endodontic or apexification methods: a retrospective study. *J Endod* 2012;**38**:1330–6.
9. Lee W, Oh JH, Park JC, Shin HI, Baek JH, Ryoo HM, et al. Performance of electronspun poly(ε-caprolactone) fiber meshes used with mineral trioxide aggregates in a pulp capping procedure. *Acta Biomater* 2012;**8**:2986–95.
10. Torabinejad M, Watson TF, Pitt Ford TR. Sealing ability of mineral trioxide aggregate when used as a root end filling material. *J Endod* 1993;**19**:591–632.
11. Purra AR, Ahangar FA, Chadgal S, Farooq R. Mineral trioxide aggregate apexification: a novel approach. *Conserv Dent* 2016;**19**:377–80.
12. Jang JH, Kang M, Ahn S, Kim S, Kim W, Kim Y, et al. Tooth discoloration after the use of new pozzolan cement (Endocem) and mineral trioxide aggregate and the effects of internal bleaching. *J Endod* 2013;**39**:1598–602.
13. Yang XB, Roach HI, Clarke NM, Howdle SM, Quirk R, Shakesheff KM, et al. Human osteoprogenitor growth and differentiation on synthetic biodegradable structures after surface modification. *Bone* 2001;**29**:523–31.
14. Yashimoto H, Shin YM, Terai H, Vacanti JP. A biodegradable nanofiber scaffold by electrospinning and its potential for bone tissue engineering. *Biomaterials* 2003;**24**:2077–82.
15. Chong EJ, Phan TT, Lim IJ, Zhang YZ, Bay BH, Ramakrishna S, et al. Evaluation of electronspun PCL/gelatin nanofibrous scaffold for wound healing and layered dermal reconstitution. *Acta Biomater* 2007;**3**:321–30.
16. Schnell E, Klinkhammer K, Balzer S, Brook G, Klee D, Dalton P, et al. Guidance of glial cell migration and axonal growth on electronspun nanofibers of poly-epsilon-caprolactone and a collagen/poly-epsilon-caprolactone blend. *Biomaterials* 2007;**28**:3012–25.
17. Ma PX. Biomimetic materials for tissue engineering. *Adv Drug Deliv Rev* 2008;**60**:184–98.
18. Mohan N, Nair PD. Polyvinyl alcohol-poly(caprolactone) semi IPN scaffold with implication for cartilage tissue engineering. *J Biomed Mater Res B Appl Biomater* 2008;**84**:584–94.
19. Pektok E, Nottelet B, Tille JC, Gurny R, Kalangos A, Moeller M, et al. Degradation and healing characteristics of small diameter poly(epsilon-caprolactone) vascular grafts in the rat systemic arterial circulation. *Circulation* 2008;**118**:2563–70.
20. Lee LW, Hsiao SH, Hung WC, Lin YH, Chiang CP. Clinical outcomes for teeth treated with electrospun poly ε-caprolactron fiber meshes/mineral trioxide aggregate direct pulp capping. *J Endod* 2015;**41**:628–36.
21. Portenier I, Waltimo T, Ørstavik D, Haapasalo M. Killing of *Enterococcus faecalis* by MTAD and chlorhexidine digluconate with or without cetrimide in the presence or absence of dentine powder or BSA. *J Endod* 2006;**32**:138–41.
22. Zehnder M. Root canal irrigants. *J Endod* 2006;**32**:389–98.
23. Camps J, Pommel L, Aubut V, Verhille B, Satoshi F, Lascola B, et al. Shelf life, dissolving action, and antibacterial activity of a neutralized 2.5% sodium hypochlorite solution. *Oral Surg Oral Med Oral Pathol Oral Radiol Endod* 2009;**108**:e66–73.
24. Peters OA, Peters CI, Basrani B. Cleaning and shaping the root canal system. In: Hargreaves KM, Berman LH, editors. *Cohen's pathways of the pulp*. 11th ed. St. Louis: Elsevier; 2016. p. 254–7.
25. Walmsley AD. Ultrasound and root canal treatment: the need for scientific evaluation. *Int Endod J* 1987;**20**:105–11.
26. Okiji T, Yoshiba K. Reparative dentinogenesis induced by mineral trioxide aggregate: review from the biological and physicochemical points of view. *Int J Dent* 2009;**2009**:464280.
27. Takita T, Hayashi M, Takeichi O, Ogiso B, Suzuki N, Otsuka K, et al. Effect of mineral trioxide aggregate on proliferation of cultured human dental pulp cells. *Int Endod J* 2006;**39**:415–22.
28. Danesh F, Vahid A, Jahanbani J, Mashhadiabbas F, Arman E. Effect of white mineral trioxide aggregate compared with biomimetic carbonated apatite on dentine bridge formation and inflammatory response in a dental pulp model. *Int Endod J* 2012;**45**:26–34.

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29. Modareszadeh MR, Di Fiore PM, Tipton DA, Salamat N. Cytotoxicity and alkaline phosphatase activity evaluation of endosequence root repair material. *J Endod* 2012;**38**:1101—5.
30. Guven EP, Taşlı PN, Yalvac ME, Sofiev N, Kayahan MB, Sahin F. In vitro comparison of induction capacity and biomineralization ability of mineral trioxide aggregate and a bioceramic root canal sealer. *Int Endod J* 2013;**46**:1173—82.
31. Daltoe MO, Paula-Silva FW, Faccioli LH, Gatón-Hernández PM, De Rossi A, Bezerra Silva LA. Expression of mineralization markers during pulp response to biodentine and mineral trioxide aggregate. *J Endod* 2016;**42**:596—603.
32. Shi S, Bao ZF, Liu Y, Zhang DD, Chen X, Jiang LM, et al. Comparison of *in vivo* dental pulp responses to capping with iRoot BP Plus and mineral trioxide aggregate. *Int Endod J* 2016;**49**:154—60.
33. Yang X, Yang F, Walboomers XF, Bian Z, Fan M, Jansen JA. The performance of dental pulp stem cells on nanofibrous PCL/gelatin/nHA scaffolds. *J Biomed Mater Res A* 2010;**93**:247—57.
34. Sonoyama W, Liu Y, Yamaza T, Tuan RS, Wang S, Shi S, et al. Characterization of the apical papilla and its residing stem cells from human immature permanent teeth: a pilot study. *J Endod* 2008;**34**:166—71.
35. Pradhan DP, Chawla HS, Gauba K, Goyal A. Comparative evaluation of endodontic management of teeth with unformed apices with mineral trioxide aggregate and calcium hydroxide. *Pediatr Dent* 2006;**73**:79—85.
36. El-Meligy OA, Avery DR. Comparison of apexification with mineral trioxide aggregate and calcium hydroxide. *Pediatr Dent* 2006;**28**:248—53.

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