ARTICLE 3

CASE REPORTS

MINERAL TRIOXIDE AGGREGATE: A NEW MATERIAL FOR ENDODONTICS

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A B S T R A C T

Background. Mineral trioxide aggregate, or MTA, is a new material developed for endodontics that appears to be a significant improvement over other materials for procedures in bone. It is the first restorative material that consistently allows for the overgrowth of cementum, and it may facilitate the regeneration of the periodontal ligament.

Case Description. The authors present five cases in which MTA was used to manage clinical problems. These included vertical root fracture, apexification, perforation repair and repair of a resorptive defect. In each case, MTA allowed bone healing and elimination of clinical symptoms.

Clinical Implications. Materials such as zinc oxide-eugenol cement and resin composite have been used in the past to repair root defects, but their use resulted in the formation of fibrous connective tissue adjacent to the bone. Because it allows the overgrowth of cementum and periodontal ligament, MTA may be an ideal material for certain endodontic procedures.

Mineral trioxide aggregate, or MTA, is a new, biocompatible material with numerous exciting clinical applications in endodontics. It has been used on an experimental basis by endodontists for several years with anecdotally reported success, some of it quite impressive. MTA's approval in 1998 by the U.S. Food and Drug Administration should lead to more widespread use. The material appears to be an improvement over other materials for some endodontic procedures that involve root repair and bone healing.

Since its first description in the dental literature by Lee and colleagues[1] in 1993, MTA has been used in both surgical and nonsurgical applications, including root-end fillings,[2-5] direct pulp caps,[6-8] perforation repairs in roots[1] or furcations,[9,10] and apexification.[11,12] It also is useful for the troublesome problems of strip perforations and perforating resorptive defects. Other materials have been used for these applications: amalgam; self-curing glass ionomer temporary restorative material (Cavit, ESPE International); resin composites; glass ionomer cement; zinc oxide-eugenol, or ZOE, with polymer reinforcement (Intermediate Restorative Material, or IRM, Dentsply Int., L.D. Caulk Div.); all-purpose lining and cement such as SuperEBA (Harry J. Bosworth Co.); gutta-percha; and zinc oxide-eugenol, but with unpredictable results.[13] MTA may be the ideal material for use against bone, because it is the only material that consistently allows for the overgrowth of cementum and formation of bone, and it may facilitate the regeneration of the periodontal ligament.[4,5,9,12]

In this article, we review the current dental literature on MTA, discussing its physical and chemical properties and clinical characteristics. We present five clinical cases to demonstrate some of its uses.

COMPOSITION AND PHYSICAL PROPERTIES

MTA is a powder consisting of fine hydrophilic particles of tricalcium silicate, tricalcium aluminate, tricalcium oxide and silicate oxide. It also contains small amounts of other mineral oxides, which modify its chemical and physical properties. Hydration of the powder results in a colloidal gel that solidifies in approximately three hours. Bismuth oxide powder has been added to make the aggregate radiopaque. Electron probe microanalysis of MTA powder showed that calcium and phosphorus are the main ions present.[14]

MTA has a pH of 12.5 after setting, similar to calcium hydroxide, or $Ca(OH)_2$.[14] This may impart some antimicrobial properties.[15] The material has low solubility[14] and a radiopacity slightly greater than that of dentin.[16] Because it has low compressive strength,[14] it should not be placed in functional areas.

IN VITRO LEAKAGE STUDIES

Microleakage is considered an important factor in success or failure of root-end fillings and perforation repairs. Torabinejad and colleagues[17] found no marginal gaps in root-end fillings with MTA, while they found gaps ranging from 3.8 to 14.9 microns with amalgam, SuperEBA and IRM. In another study, Torabinejad and colleagues[18] found that MTA leaked significantly less than amalgam and SuperEBA ($P < .001$) when placed in 3-millimeter root-end preparations. Similar results were reported by Fischer and colleagues.[19] In a study by Torabinejad and colleagues[20] on the effects of blood on root-end fillings, MTA leaked significantly less than amalgam, IRM and SuperEBA ($P < .05$). IRM and SuperEBA, in particular, did not seal well in the presence of blood contamination. Bates and colleagues[21]—using a fluid filtration device to test the sealing properties of MTA, SuperEBA, and amalgam—found that MTA, when used as a root-end filling material, was superior to amalgam ($P < .05$) and comparable with SuperEBA in preventing microleakage. Wu and colleagues[22] found that the seal created with MTA in root-end fillings lasts for at least a year.

Torabinejad and colleagues[23] evaluated coronal microleakage of bacteria in the canals of single-rooted teeth that had 3-mm root-end fillings of either MTA, amalgam, SuperEBA or IRM. They found that MTA leaked significantly less than the other materials ($P < .05$). They saw no leakage in any MTA-filled tooth at the end of the study (day 90), whereas the other materials began to leak between days 15 and 34. A similar study by Adamo and colleagues[24] found no difference in bacterial penetration with MTA, SuperEBA, dentin-bonded amalgam and composite. In a test of coronal microleakage with endotoxin, Tang and colleagues[25] showed that MTA was superior to amalgam and IRM.

In a study by Nakata and colleagues,[26] the researchers found MTA to be superior to amalgam ($P < .0005$) in preventing leakage of *Fusobacterium nucleatum* past furcation repairs. Lee and colleagues[1] reported that in lateral root perforations, MTA leaked significantly less than IRM or amalgam ($P < .05$). This study also showed that overextrusion of material into the perforation site was much less a problem with MTA than it was with IRM and amalgam.

BIOCOMPATIBILITY

Torabinejad and colleagues performed a series of biocompatibility studies with MTA. Kettering and Torabinejad[27] found it to be nonmutagenic, and Torabinejad and colleagues[28] found it to be less cytotoxic than SuperEBA and IRM. In animal studies, MTA was the only material studied that allowed cementum overgrowth.[4,5] It was found to be biocompatible when implanted into guinea pigs,[2,3,29] dogs[4] and monkeys,[5] and was more biocompatible than amalgam, SuperEBA or IRM. In vitro studies of human osteoblasts showed that MTA stimulated cytokine release[30] and interleukin production.[31] These studies suggest that MTA is not just an inert material but may actively promote hard-tissue formation.

ANTIMICROBIAL PROPERTIES

Torabinejad and colleagues[15] tested MTA, amalgam, ZOE and SuperEBA against nine facultative bacteria and seven strict anaerobes. MTA was found to have an antibacterial effect on five of nine facultative bacteria but no effect on any of the strict anaerobes. The other materials had similar effects. The researchers concluded that none of the test materials had all of the antibacterial effects desired for a root-end filling material.

IN VIVO STUDIES

Torabinejad's research group compared the responses in monkeys (Pitt Ford and colleagues[6])

Figure 1. Horizontal root fractures were present in both maxillary central incisors.

and dogs (Abedi and colleagues[7]) to direct pulp caps with MTA or $Ca(OH)_2$ and found less inflammation and better dentin bridge formation with MTA. A study by Myers and colleagues[8] evaluated MTA and $Ca(OH)_2$ as pulp-capping materials in dogs and found that there was no statistically significant difference ($P > .05$) in pulpal status or dentin bridging between the two materials.

Pitt Ford and colleagues[9] repaired intentional furcation perforations in mandibular premolars of dogs either immediately or four months after perforation with either MTA or amalgam. They concluded that MTA is more suitable for furcation repair than amalgam, especially if the repair is done immediately. In two patients, Arens and Torabinejad[10] reported osseous repair of furcation perforations repaired with MTA.

Shabahang and colleagues[11] compared MTA, osteogenic protein-1 and $Ca(OH)_2$ for apexification in dogs. They found that MTA induced hard-tissue formation more often than did the other test materials and concluded that MTA was suitable for use as an apical barrier for apexification in immature roots.

CASE REPORTS

Case 1. A 24-year-old man complained of "loose" central incisors after having been hit in the mouth with a softball 10 days before. Aside from mobility, the patient had no other complaints. A clinical examination revealed that both maxillary central incisors had Class III mobility. The gingiva was quite inflamed, but probing depths were less than 3 mm. The central incisors demonstrated no response to cold, but the other incisors responded normally. The central incisors were slightly tender to percussion. A periapical radiograph showed horizontal root fractures in both central incisors (Figure 1). The clinician made a preliminary diagnosis of pulpal necrosis for both teeth.

The clinician stabilized the teeth with a rigid arch wire and resin composite and then isolated them with a rubber dam. Access was made without anesthesia, and pulpectomies were performed to the fracture sites. The pulps in the coronal segments were both necrotic. Because the pulps apical to the fractures were responsive to gentle probing with a file and usually remain vital in horizontal root fractures,[32] they were not treated. $Ca(OH)_2$ (Pulpdent Paste, Pulpdent Corp.) was placed in the coronal segments.

The patient remained asymptomatic for the next six weeks, at which time he returned for removal of the splint. He had no complaint and no change in probing depths or in results of clinical tests. The teeth were not tender to percussion. There were no sinus tracts or other signs of pathology clinically or radiographically. The clinician removed the $Ca(OH)_2$ from the canals, dried the canals and placed MTA barriers to the fracture sites. He then obturated the canals with gutta-percha and removed the fixation (Figure 2). The patient's postoperative course was uneventful. At a six-month recall visit, the central incisors were asymptomatic and responded normally to percussion, palpation and pressure, but remained slightly mobile.

Figure 2. After splint stabilization for six weeks, apical barriers were placed with mineral trioxide aggregate and the root canal therapy was completed with gutta-percha and sealer. The wire splint was then removed.

Case 2. A 29-year-old man was referred by a general dentist who had noted root resorption in the maxillary right central incisor on a radiograph (Figure 3). The patient had been assaulted 18 months earlier, which had resulted in subluxation of several incisors. The

Figure 3. The patient was referred with a large resorptive lesion in the root of his maxillary right central incisor. A pulpectomy was performed and progressive débridement of granulation tissue was accomplished by monthly irrigation with sodium hypochlorite and placement of calcium hydroxide.

patient was asymptomatic and without complaint. He had large restorations and caries in many of his teeth and generalized gingivitis. The maxillary right central incisor was unresponsive to cold; the other teeth in the area responded normally. There were no probing depths greater than 4 mm, and it was not possible to probe into the resorptive defect through the sulcus. No sinus tract was present. The clinician made a diagnosis of pulpal necrosis with root resorption, probably external.

The clinician administered anesthetic, placed a rubber dam and gained access through the lingual surface of the unresponsive tooth. Working length was established, and the clinician performed a pulpectomy. It quickly became evident that the resorption had resulted in communication between the pulp and adjacent bone, because it was not possible to dry the canal. The clinician placed $Ca(OH)_2$.

At the next appointment two weeks later, the patient reported no symptoms or complaints. The clinician removed the $Ca(OH)_2$, irrigated the canal with sodium hypochlorite and then dried the canal. He inspected the resorptive defect inside the tooth with the aid of a surgical operating microscope. The defect included the distal and lingual aspects of the root and was filled with granulation tissue. The clinician placed new $Ca(OH)_2$ in the tooth.

The patient returned at one-month intervals for the next three months. At each appointment, the clinician took a preoperative radiograph, irrigated the canal with sodium hypochlorite, dried it, replaced the $Ca(OH)_2$ and took a postoperative radiograph. The radiographs showed that the $Ca(OH)_2$ expanded further into the resorptive lesion after each appointment, indicating that additional débridement of the granulation tissue was occurring. After the third monthly appointment, a radiograph showed that the $Ca(OH)_2$ had expanded to fill the resorptive lesion and extended into the bone.

The patient returned a month later for repair of the resorptive defect. Throughout this process, the patient remained asymptomatic and free of clinical signs of infection. Probing depths did not change. The adjacent teeth responded normally to clinical tests. The clinician removed the bulk of the $Ca(OH)_2$ with files, irrigated the canal with sodium hypochlorite and dried the canal. The canal apical to the resorptive lesion was obturated

Figure 4. After three months, débridement of the lesion was complete. The calcium hydroxide was removed, the canal was dried and the resorptive defect was repaired internally with MTA. The clinician placed a post that extended apically to the resorptive defect and restored the tooth with resin composite in preparation for placement of a crown.

with gutta-percha and sealer. With the aid of the microscope, the clinician carefully removed the $Ca(OH)_2$ from the resorptive defect with a small spoon excavator. He pressed a thick mix of MTA into the defect. Residual $Ca(OH)_2$ in the bone and outer portions of the defect prevented excessive extrusion of MTA outside the root. The clinician placed several moist paper points in the canal (moisture is necessary for MTA to set) and placed a temporary restoration in the access opening.

At the next appointment, the MTA felt hard to an explorer. The clinician prepared a post space that extended several millimeters apical to the resorptive defect. A post was cemented, and the tooth was restored with composite as an interim restoration and to serve as a buildup mate-

Figure 5. The patient was referred with a perforation into the furcation after a procedural accident during root canal therapy.

rial for a crown (Figure 4). The tooth remained asymptomatic throughout treatment and at a six-month recall visit.

Case 3. A 27-year-old man was referred for endodontic evaluation of the mandibular left first molar (Figure 5). While performing a root canal, the referring dentist had unintentionally placed Dycal (Dentsply, L.D. Caulk) in the canals after his assistant had mistaken it for Sealapex (Dentsply, L.D. Caulk), an endodontic sealer cement with packaging that looks similar to that of Dycal. As the dentist had obturated the distal canal with gutta-percha, the Dycal had hardened in the mesial canals. In trying to remove the Dycal from the mesiolingual canal, he had perforated into the furcation. At the time of the endodontic evaluation, the patient complained of tenderness to biting pressure and mild spontaneous pain.

Clinical evaluation revealed no pockets of a depth greater than 3 mm. It was not possible to probe into the furcation through the sulcus. The first molar was tender to pressure and percussion. Adjacent teeth responded normally to biting pressure, percussion and cold. There was radiographic evidence of bone loss in the area of the furcation and rarefaction in the periapical areas of the first molar. The clinician made a diagnosis of previous root canal treatment with acute and chronic periradicular periodontitis.

The clinician administered anesthetic and isolated the tooth with a rubber dam. He removed the filling materials from all three canals and was able to visualize the perforation with the surgical operating microscope. The distal and mesiofacial canals were obturated routinely with gutta-percha and sealer. The clinician then obturated the mesiolingual canal apical to the perforation and packed the coronal portion of the canal with MTA to the orifice. An internal matrix barrier was not used, and some of the MTA extruded into the furcation.

The tooth became asymptomatic within several days. At the three-week recall visit, the tooth was free of spontaneous pain and responded normally to percussion, palpation and biting pressure. The clinician placed an amalgam buildup.

The tooth remained asymptomatic at the six-month recall visit, and there were no probing depths greater than 3 mm. There were no signs or symptoms of pathology, and the radiolucency in the furcation appeared to have resolved (Figure 6).

Case 4. A 72-year-old man with a temporary crown on the mandibular right first molar was experiencing biting tenderness and intermittent spontaneous pain. A strip perforation had occurred in the mesiofacial canal during root canal treatment one month before. At that time, Class I furcation involvement was present on the facial aspect of the tooth, which had a probing depth of 4 mm. No bone loss was radiographically evident in the furcation. The dentist had decided to complete the endodontic therapy and recall the patient in a month to evaluate the situation. At the one-month recall visit, the tooth's condition had worsened. A radiograph showed a significant radiolucency in the furcation, and the probing depth was 8 mm (Figure 7). The tooth was tender to percussion and biting pressure, and the patient reported mild spontaneous pain. The diagnosis was perforation during previous root canal treatment and acute periradicular periodontitis.

The clinician administered anesthetic, placed a rubber dam and removed the gutta-percha from the mesiofacial canal to a point apical to the perforation. The clinician visualized the per-

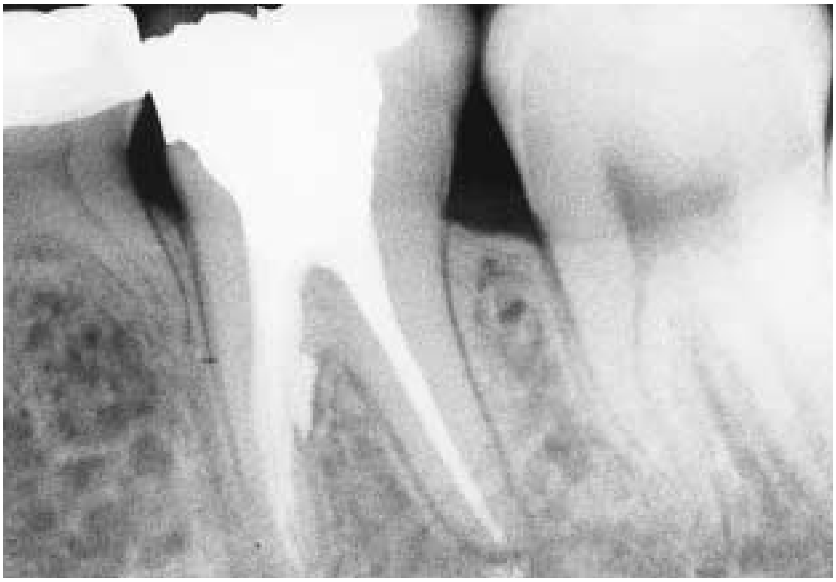

Figure 6. The tooth was asymptomatic and the periodontium was healthy at a six-month recall visit despite extrusion of the mineral trioxide aggregate into the furcation.

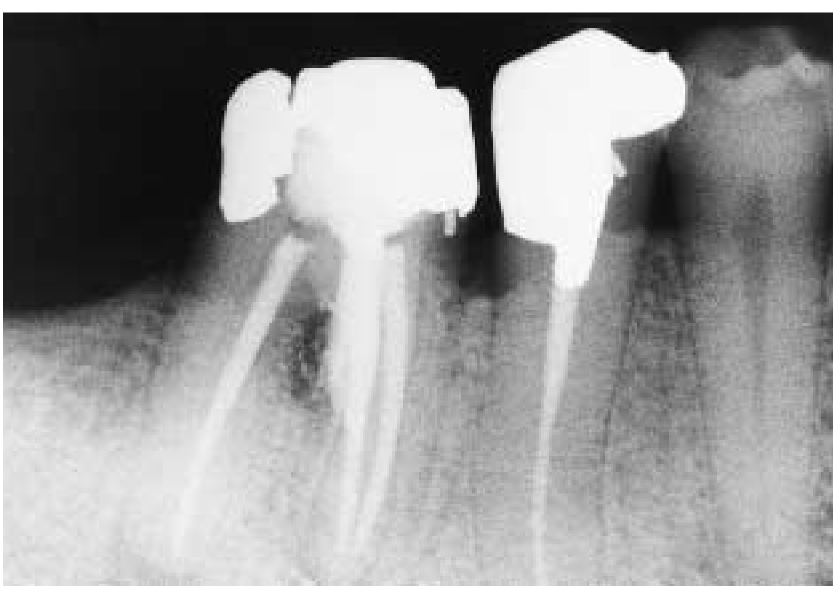

Figure 7. A strip perforation had occurred in the mesiobuccal canal during root canal therapy. One month later, significant bone loss was evident in the furcation and the probing depth had increased from 4 millimeters to 8 mm.

foration and packed the coronal portion of the canal with MTA to seal the perforation. He pushed a combination of gutta-percha, sealer and MTA into the furcation during obturation, so a buccal flap was reflected, and he removed the excess material from the furcation. With the aid of the surgical operating microscope and micromirrors, the clinician visualized the perforation through the furcation on the distolingual surface of the mesiobuccal root; he then created a smooth repair surface (Figure 8). He repositioned the buccal tissue to its original location and placed sutures. The patient returned two days later for suture removal.

At a two-week recall visit, the gingiva had healed nicely. The tooth remained tender to percussion and biting pressure, but the patient reported no spontaneous pain. No probing was performed.

At a six-month recall visit, the patient was asymptomatic. There was no spontaneous pain, and the tooth responded normally to pressure and percussion. There was radiographic evidence of new bone formation in the furcation, and the probing depth in the buccal furcation was again 4 mm (Figure 9). The patient reported that the tooth had remained mildly symptomatic for a period of time after the surgery, but had been asymptomatic for the past several months.

Case 5. A 29-year-old woman was referred for endodontic evaluation with a chief complaint of a discolored front tooth that had become noticeably worse over the past year. She denied any history of pain or swelling associated with the tooth. Clinical evaluation indicated that the maxillary right central incisor had a dark gray discoloration. The periodontal assessment was normal, although the mucosa over the root appeared cyanotic. The tooth was not responsive to thermal pulp testing, and a sinus tract was present in the mucosa distal to the tooth (Figure 10). A radiograph showed a blunderbuss open apex with thin dentinal walls.

The proposed treatment plan addressed the concerns of the chronic infection associated with a nonvital pulp, apical management for obturation and

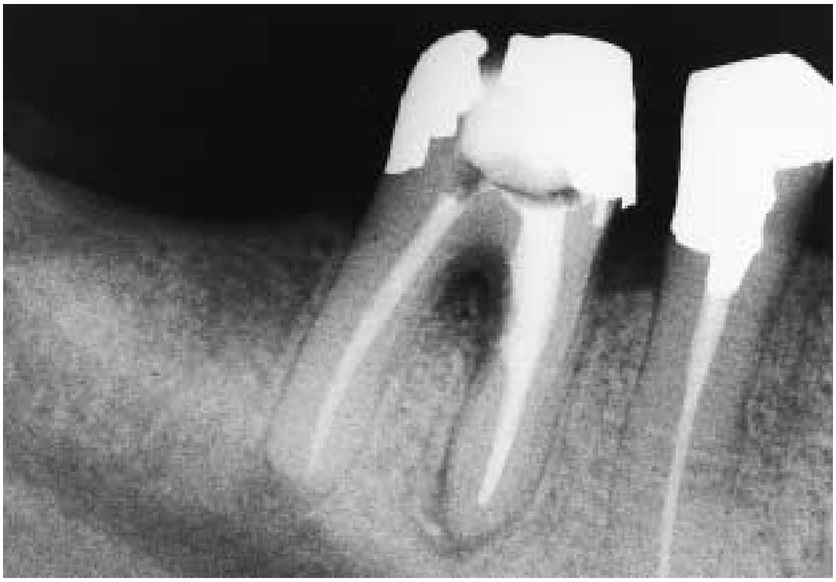

Figure 8. Gutta-percha, sealer and mineral trioxide aggregate, or MTA, were pushed into the furcation during internal repair of the perforation. A buccal flap was reflected and excess material was removed from the furcation. The MTA was smoothed flush with the external surface of the root.

Figure 9. At a six-month recall visit, there was radiographic evidence of bone fill in the furcation and probing depths were back to 4 millimeters. The patient was asymptomatic.

achieving an apical seal, and the discoloration and restoration of the tooth. The options for root-end management included periapical surgery with placement of a root-end filling, classic apexification with long-term $Ca(OH)_2$ to induce formation of an osteodentin apical barrier, or placement of an artificial apical plug or barrier.

The clinician used a split-dam technique for isolation during all endodontic procedures. At the first appointment, access was made, working length was established, and the root canal space was débrided and irrigated with sodium hypochlorite. The clinician placed $Ca(OH)_2$ and temporized the tooth. After three weeks, the sinus tract remained open, but no exudate could be expressed. The clinician noted an improvement in the color and texture of the mucosa labial to the root of the tooth. He replaced the $Ca(OH)_2$ and temporized the tooth with IRM.

At the third appointment, two weeks later, the sinus tract had closed, the labial mucosa appeared normal, and the tooth remained periodontally intact and was asymptomatic. Rather than continue apexification for an indeterminate period, the clinician decided to place an apical barrier of MTA and complete the root canal. He cleared the root canal space of the $Ca(OH)_2$ paste, irrigated it and dried it. The clinician prepared a thick mix of MTA and saline and delivered it into the canal. He lightly condensed the mass using the back end of several paper points, leaving a minimal thickness of 2 mm. The canal was filled with $Ca(OH)_2$ paste, and the tooth was temporized to allow the MTA to set overnight.

The next day, the MTA barrier felt hard to an explorer. The root canal space was obturated with ZOE sealer and vertical condensation of injectable thermoplasticized gutta-percha. Internal bleaching was accomplished over the following month using a walking-bleach technique. The clinician used a bonded resin composite to restore the access cavity. At nine- and 20-month (Figure 11) recall visits, the tooth was asymp-

Figure 10. Diagnostic radiograph with gutta-percha point tracing the sinus tract. Note the immature root development and open blunderbuss apex, which represents a tooth development age of approximately 7 years.

tomatic, and normal periapical bony architecture was present.

DISCUSSION

MTA is supplied as a gray powder. The manufacturer recommends that it be mixed with sterile water into a thick, grainy paste. Some clinicians report success in mixing MTA with anesthetic or other sterile liquids, but the effects other liquids may have on MTA's physical, chemical and biological properties are unknown. Once mixed, it may be carried with a small amalgam carrier or messing gun or placed with a small hand instrument. If moisture is present in the preparation or resorptive defect, the MTA becomes "soupy" and difficult to condense. Moisture can be drawn out of the MTA after placement with a dry paper point or cotton pellet. MTA is often pressed into the desired location and not really condensed.

In preparing the site to receive the MTA, the clinician should follow several guidelines. All irrigation should be performed before the MTA is placed. Any irrigation after placement will cause significant washout of the material. The preparation or resorptive defect does not have to be perfectly dry, but most of the fluid should be removed. If MTA is placed from inside the tooth, a moist cotton pellet or paper point should be placed against it, because the presence of moisture is essential for the material to set. The access cavity is then closed.

MTA requires several hours to set into a hard mass. Most internal repairs with MTA require a second visit to complete the root canal therapy or restoration. Gutta-percha sometimes can be condensed immediately if the proper resistance form is present and moisture is available from outside the tooth, such as in Case 1.

In addition to endodontic applications, MTA also may have some uses in periodontics. An interesting question is whether MTA can be used in conjunction with bone-grafting procedures. For example, if a perforation has caused an infrabony periodontal defect, the perforation perhaps could be repaired with MTA, then a grafting procedure performed to treat the periodontal defect. This is an area for further study.

MTA appears to be advantageous for repair of perforations and resorptive lesions. Deposition of cementum and establishment of a periodontal ligament is preferable to the formation of fibrous tissue that occurs with other materials. The cementum may form a biological seal that is similar to that of a normal root surface. There is only one

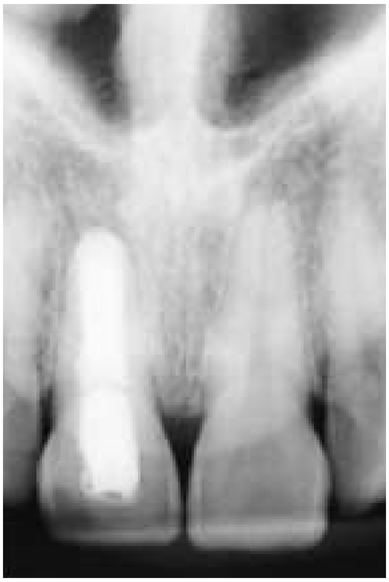

Figure 11. An artificial barrier of mineral trioxide aggregate was placed and the canal was obturated. At a 20-month recall visit, the periapical architecture was intact and a periodontal ligament space was evident.

report of cementum formation over another material.[33]

The procedures described in this article often require special instrumentation and the improved visualization provided by the surgical operating microscope. These suggested techniques are not without their difficulties. Some of these procedures may not be within the scope of practice for every dentist, in which case referral to a specialist would be appropriate.

CONCLUSION

MTA is a promising material with an expanding foundation of research. To date, however, the majority of the work has been done by Torabinejad and colleagues, who were involved in the material's development. Their research is very thorough and compelling, but there is a need for more studies by independent researchers. In addition, there have been no published human studies with

MTA. Impressive results in animal models do not always translate into impressive results in humans, so there is a need for controlled clinical studies on humans. Several of the cases presented in this article have follow-up periods of less than one year. The success of a new material can best be judged with long-term studies. ■

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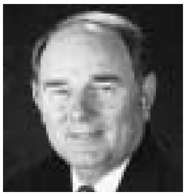

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