Bioceramic Materials for Management of Endodontic Complications

Saulius Drukteinis

1 Introduction

Prior to the introduction of mineral trioxide aggregate (MTA), the success rates of perforation repair were relatively low due to poor biocompatibility, sealing ability, high cytotoxicity, and hydrophobic properties of the used materials [1]. MTA has changed existing standards in the management of endodontic complications, vital pulp therapy, and regenerative endodontic procedures. However, MTA has a number of limitations, such as problems with mixing, long setting time, difficult handling characteristics and complicated delivery of the material, discoloration of the tooth structure, and the presence of the toxic elements, making the use of this material challenging for many clinicians [2, 3].

During the last decade, the modified hydraulic calcium silicate-–based materials for use as root canal sealers, fillers, or root repair materials were introduced to the market [4, 5]. Modifications of the original MTA improved physicochemical, biological properties, and facilitated clinical applicability [6, 7]. The currently available materials are launched as flowable pastes or solid-putty consistency materials. The main biological properties of these materials are quite similar, while the main differences are related to the handling characteristics and application indications [8].

S. Drukteinis (✉)
Institute of Dentistry, Vilnius University, Vilnius, Lithuania

2 Materials Used for Management of Endodontic Complications

There is a wide range of materials available for management of endodontic complications including flowable materials that are launched as premixed and ready-to-use pastes or powder/liquid formulations. Some materials are only suggested to be used as root repair materials in conjunction with different application techniques, while other materials are proposed as sealers or biological fillers and can be used for root canal obturation as well as management of endodontic complications and root repair. The main advantages of flowable hydraulic calcium silicate–based materials are easy manipulation and clinical applicability [8, 9].

2.1 iRoot®BP, EndoSequence® BC RRM™, and TotalFill® BC RRM™ Paste

iRoot®BP, EndoSequence® BC RRM™, and TotalFill® BC RRM™ were the first paste-type and ready-to-use premixed hydraulic calcium silicate–based materials developed for root repair and surgical applications [10, 11] (Fig. 1a). These

S. Drukteinis, J. Camilleri (eds.), *Bioceramic Materials in Clinical Endodontics*,
https://doi.org/10.1007/978-3-030-58170-1_6

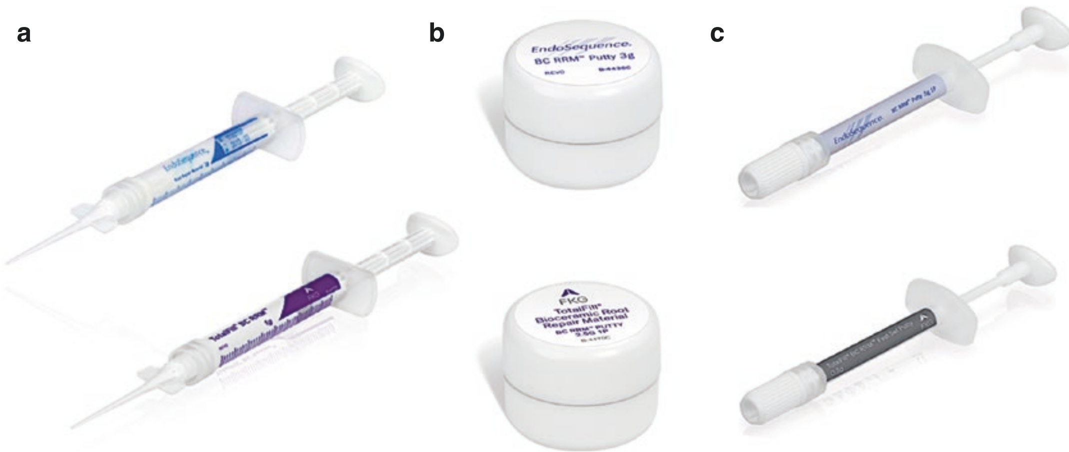

Fig. 1 Different formulations of EndoSequence® BC RRM™ (*upper row*) and TotalFill® BC RRM™ (*lower row*) root repair materials: paste (**a**), putty (**b**), and fast set putty (**c**)

materials are sold under different brand labels; however, they have identical chemical composition, possesses the same physical, biological properties, handling characteristics, and are equally clinically effective [10, 12]. Materials do not shrink in wet environment are radiopaque, aluminum-free and based on a calcium silicate composition, which requires the presence of water to set and harden. The primary difference between RRM paste and BC sealer is that RRM paste contains more filler particles, is more viscous, and has different radiopacifier [9, 11, 13]. These materials are available as root repair pastes in preloaded syringes. The preloaded syringe also has flexible intracanal tips that facilitate its placement in clinical situations. According to the manufacturer's instructions, they have a working time of 30 min and a setting reaction initiated by moisture with a final set achieved approximately within 4 h and is highly dependable on the moisture inside the root canals. The amount of moisture necessary to complete the setting reaction is naturally present in the dentin tubules. Therefore, it is not needed to add moisture in the root canal before placing these materials; however, the root canals should not be excessively desiccated (for example, using alcohol). The indications for use include repair of root perforation, repair of root resorption, root-end (retrograde) filling, apexification, and pulp capping [14, 15].

2.2 iRoot®BP Plus, EndoSequence® BC RRM™, and TotalFill® BC RRM™ Putty

All these materials are convenient ready-to-use white hydraulic premixed putty-type materials developed for permanent repair of large and more easily accessible perforations, resorptions, apexification, and retrofilling [16]. Materials come in the form of premixed condensable putty; their consistency is slightly thicker and more malleable than RRM pastes [17].

As their original formulations, putty materials are radiopaque and aluminum-free materials based on a calcium silicate composition, which requires the presence of water to set and harden [11]. Materials do not shrink during setting and demonstrate excellent physical properties. Their major inorganic components include C_3S, C_2S, and calcium phosphates [18]. Because the materials are premixed with nonaqueous but water-miscible carriers, they do not set during storage and hardens only on exposure to a wet environment [19]. Similar to the paste, the RRM Putty working time is more than 30 min and setting time is 4 h [20]. EndoSequence® BC RRM™ and TotalFill® BC RRM™ Putty are packaged in a preloaded jar [15] (Fig. 1b), while iRoot®BP Plus can be packed in a jar or syringe (Fig. 2a).

Fig. 2 The iRoot®BP Plus (**a**) and Well-Root™ PT (**b**) putty-type hydraulic calcium silicate–based materials for repair procedures and management of endodontic complications

2.3 iRoot®FS, EndoSequence® BC RRM™, and TotalFill® BC RRM™ Fast Set Putty

iRoot®FS, EndoSequence® BC RRM™, and TotalFill® BC RRM™ Fast Set Putty are modifications of original formulations of the flowable RRM pastes [10, 15]. These materials have the same properties and radiopacity, but their chemical composition differs slightly, which enables materials to harden approximately in 20 min [12, 13]. Due to the accelerated hydration reaction and reduced setting time, materials are extremely resistant to washout, which makes them superior in some specific clinical situations [21].

As their original formulations, these materials are ready to use and EndoSequence® BC RRM™ and TotalFill® BC RRM™ are packed in Sanidose™ syringes (Fig. 1c). The ideal consistency, malleable, and ease of manipulation make these materials usable for various clinical applications [11]. Main clinical advantages are high biocompatibility, bioactivity, and osteogenic potential [22, 23]. Fast set putties possess antibacterial activity, high alkalinity (up to 12 pH) are hydrophilic and do not cause significant discoloration of the hard tissue of the teeth [10, 24].

2.4 Well-Root™ PT

Well-Root™ PT (Vericom, Gangwon-Do, Korea) (Fig. 3b) is a ready to use, premixed, bioceramic paste developed for pulp capping, permanent root canal repair, and surgical applications. It is an insoluble and radiopaque material based on a calcium aluminosilicate composition, which requires the presence of water to set and harden [9]. Well-Root™ PT does not shrink during setting and demonstrates excellent physical and biological properties [25, 26]. It has been shown that material does not create an inflammatory response, promotes mineralization, and demonstrates bioactivity [9]. Some studies using EDS microanalysis, among other elements, detected peaks for sodium, magnesium, aluminum, and titanium in the material [25]. However, the clinical implication of heavy metals contained in Well-Root needs to be investigated [27]. Well-Root™ PT is supplied in packs of 10 × 0.25 g capsules and can be delivered to the application site using a special gun (Fig. 2b).

2.5 Biodentine®

Biodentine® is manufactured by Septodont (Saint-Maur-de-Fosses Cedex, France) and is composed of tricalcium silicate, calcium carbonate, and zirconium oxide as the radiopacifier, while its liquid form contains calcium chloride as the setting accelerator and water-reducing agent. Biodentine® has been launched as a bioactive dentin substitute with the mechanical properties similar to the sound dentin and can replace it both in the crown and in the root [28, 29].

Fig. 3 The package of the Biodentine® contains single-dose powder capsules and vials with a liquid

According to the manufacturer, the "Active Biosilicate Technology®" used to produce Biodentine® ensures the purity of tricalcium silicate, which is what makes this material different from the MTA, which is based on the Portland cement, containing low concentrations of different metal impurities [30, 31]. However, studies have found remains of arsenic, lead and chromium in Biodentine®, but since the release in the physiological solution is minimal, they have been considered safe [32]. Biodentine® comes as a capsule containing powder and a liquid contained in a vial (Fig. 3). According to the mixing instructions, the five drops of the liquid should be squeezed into the capsule and then mixed in an amalgamator for 30 s at a speed of 4000–4200 rotations/min. After mixing, the capsule should be opened and the material's consistency checked. If a thicker consistency is preferred, it is recommended to wait for 30 s to 1 min before checking again [33].

According to the manufacturer, the initial material's setting time is 12 min and is much shorter compared to MTA [34]. From the clinical point of view, it is very important to isolate the operating field during the placement of Biodentine® properly for these 12 min, as water or fluid contamination slows the setting of the material. It has been claimed that the faster setting of the material is related to the smaller size of the powder particles and a greater reaction area, subsequently. Meanwhile, the calcium chloride in the liquid is a strong accelerator of the setting reaction in Biodentine®, while the presence of calcium carbonate powder increases the hydration reaction of the material [35, 36]. The water-soluble polymer plays an essential role to increase powder density, as the smaller amount of the water is required to obtain the plasticized consistency of the material [31]. Finally, in Biodentine®, the zirconium oxide is added as a radiopacifier, and this is another important difference with MTA, where radiopacity is given by bismuth oxide [37, 38].

3 Temporary Bioceramic-Based Root Canal Dressing Materials

The temporary antibacterial root canal dressing materials are widely used during the endodontic treatment of the teeth with pulp necrosis and apical periodontitis as well as management of endodontic complications [39]. The calcium hydroxide was the material of choice for the interappointment root canal filling used to maximize the root canal disinfection [40–42]. The BIO-C® TEMP is the first ready-to-use bioceramic-based paste for intracanal dressing (Fig. 4). According to the manufacturer, the

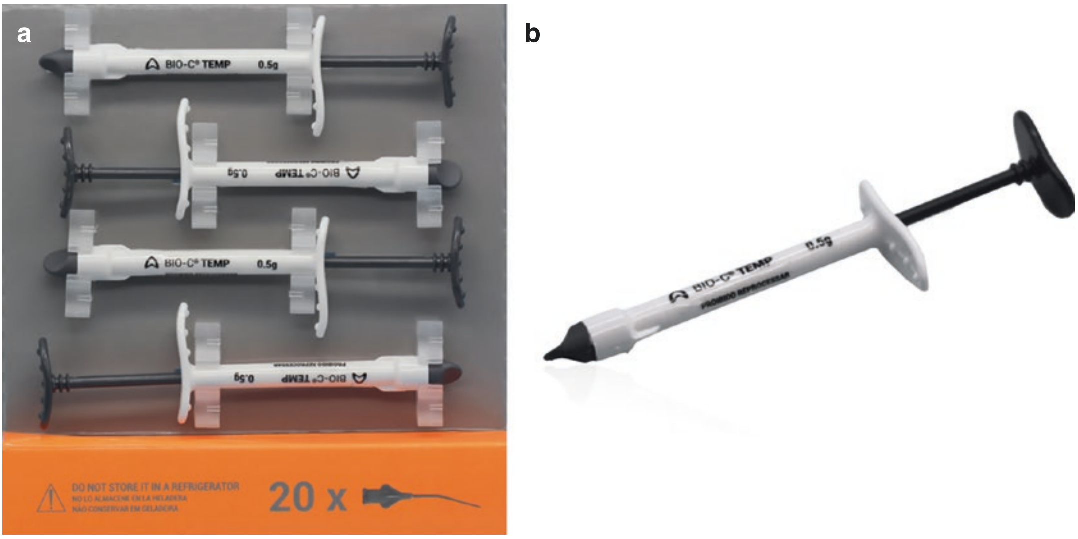

Fig. 4 The package (**a**) and the syringe (**b**) of the first temporary bioceramic-based root canal dressing material BIO-C® TEMP

material is recommended to use as a substitute for conventional calcium hydroxide dressing [43]. The indications for use are intracanal dressing for endodontic treatment in teeth with pulp necrosis and retreatments—intracanal dressing in teeth with perforations, external and internal resorptions, prior to the use of root repair materials—for the apexification procedures.

The composition of the material is calcium silicates, calcium aluminate, calcium oxide, calcium tungstate, and titanium oxide. The material is biocompatible and ready for use, has high alkalinity (pH is 12 ± 1), and radiopacity (9 mm of the aluminum) [43]. The paste is launched in 0.5 g syringes and can be delivered into the root canal via plastic tip cannula, attached to the syringe as the majority of the premixed bioceramic materials.

Before application, the root canal should be irrigated using standard protocols and dried with absorbent paper points. It is recommended to discard the material at the beginning of the syringe, as it may be a little hard. After connection of the applicator tip to the syringe, the tip should be inserted up to 1–2 mm from the established working length. BIO-C® TEMP should be applied through gradual retraction of the syringe to obtain a complete filling of the canals. Any excess of the paste should be removed from the pulp chamber and temporary filling material placed into endodontic access. The final removal of BIO-C® TEMP before root canal obturation should be performed using sodium hypochlorite and 17% EDTA solution subsequently, which is recommended to activate with an ultrasonic tip in three cycles of 10 s.

It should be mentioned that the product is sensitive to moisture, so the packaging should be properly closed with adequate pressure to prevent dryness. The paste should not be stored in the refrigerator. According to the manufacturer, the paste is easily washable out from the root canals, and the additional irrigation with citric acid is not necessary. It is advantageous in comparison to conventional calcium hydroxide paste, which is difficult to remove from the root canal system.

4 Apexification Procedures

The apexification procedure is performed when the pulp of the tooth with incompletely developed root becomes necrotic, and regenerative treatment procedures are not indicated or possible [44]. The main problems that face clinicians with immature permanent teeth are complicated

Fig. 5 Immature roots of a mandibular molar with a wide-open apices (**a**). The apical matrix barrier is usually created (**b**) using collagen or hemostatic material (**c**), to prevent extrusion of repair materials

cleaning-shaping and obturation procedures due to the thin root walls and lack of apical barrier [44, 45]. The walls of undeveloped roots are usually thin and very prone to fractures; therefore, mechanical preparation should be performed using minimally invasive techniques [46]. Meanwhile, there is a high risk to extrude the irrigants and obturation materials into periapical tissues because the mineralized apical barrier is absent [47] (Fig. 5a).

Calcium hydroxide has been the material of choice for multiple-visit apexification procedure for a few decades with acceptable success rates [48]. However, the compromised coronal seal between visits and possible recontamination, as well as increased risks of the fracture of the root and crown, were the main clinical concerns, decreasing the success rate of the apexification [48]. For these reasons, the single- or two-appointment apexification using MTA has been introduced and widely used for many years with a very high clinical success rate [49]. However, drawbacks of mixing and hardening, long setting time, difficult handling characteristics and complicated delivery of the material, discoloration of the tooth hard tissues, and the presence of the toxic elements made the use of this material challenging for many clinicians [16].

During the last decade, the hydraulic calcium silicate–based materials were used for apexification procedures with equal success as original MTA [14, 50]. The improved physicochemical and biological properties, easier clinical applicability, and no effect on the color of the hard tissues of the tooth make these materials superior to the original Portland cement–based MTA [6, 47]. The semi-solid hydraulic calcium silicate–based materials like Biodentine®, iRoot®BP Plus, EndoSequence® BC RRM™, and TotalFill® BC RRM™ Putty were used as apical plugs in the management of the open apices [13, 51]. The clinical procedure is very similar to the technique when the MTA is used as an apical plug. However, before the placement of the material, the obturation technique should be considered by the clinician. These materials can be used just as an apical 4–6 mm plugs [52]; the whole root canal up to the orifice can be filled, or the whole root canal and an endodontic access-tooth crown can be filled and restored [13]. If the endodontic access is filled, the materials are used as a dentine substitute, expecting to reinforce tooth crown and root. It has been shown that complete root canal and endodontic access filling with Biodentine®, as a dentine substitute, increased the tooth resistance to the fractures, longevity, and survival rates [53, 54].

Due to the wide foraminal opening, the apexification procedure often requires placement of the matrix or apical barrier, to prevent or minimize the extrusion of the hydraulic calcium silicate–based materials periapically (Fig. 5b). Despite the excellent biological properties and biocompatibility of these materials, their extrusion is not recommended and should be avoided [47, 50, 55]. A number of the materials have been recommended to be used as a matrix; however, the hemostatic sponges or collagen are the most popular [45, 47, 56] (Fig. 5c). The matrix materials can be delivered to the apical-periapical region via the prepared root canal using pre-fitted gutta-percha plugger using gentle condensation of the barrier material apically. These materials are very well tolerated by periapical tissues and are resorbed within a few days [45, 56]. They perform not only as a mechanical barrier but also as a moisture control, as they protect the hydraulic calcium silicate–based materials from the contamination with tissue fluids or blood and possible washout [51].

After isolation of the tooth with a rubber dam and endo access opening, the root canal is prepared using suitable endodontic instruments and appropriate irrigants (Fig. 6a). After preparation, the root canal should be dried with paper points; however, overdrying should be avoided. The apical matrix-barrier using collagen should be established as described previously (Fig. 6b). If the material used as an apical plug is requiring mixing prior to its application (for example, Biodentine®), it should be done according to the manufacturer's recommendations. No specified preparations are needed for the premixed putty-type hydraulic calcium silicate–based materials [11]. Materials are delivered to the root canal using a suitable instrument and gently condensed with a pre-fitted plugger (Fig. 6c). The indirect sonic or ultrasonic agitation of the materials has been recommended to decrease the porosity and increase the sealability of the materials [57, 58]. However, there is a lack of solid and sufficient scientific background to support this recommendation. The X-ray should be taken after the procedure to check that the material is homogeneous and correctly positioned. If the voids in the material or inadequate length of the apical plug are detected, additional condensation should be applied, and new X-ray should be taken.

Recently, the Type 5 fast set putty materials such as iRoot®FS, EndoSequence® BC RRM™, and TotalFill® BC RRM™ Fast Set Putty were introduced and successfully used as apical plugs during apexification procedures [13]. The short setting time allows the completion of the treatment procedure in a single visit, which is advantageous in comparison to regular putty materials and is quite similar to the procedure using Biodentine® [13].

If the hydraulic calcium silicate–based materials are used just as apical plugs, the rest of the root canal should be obturated with thermoplastic gutta-percha and sealer. Usually, it is performed during the next visit, as the long setting time of the materials does not allow to finish whole apexification procedure at the single appointment. After initial setting of apical plugs, the

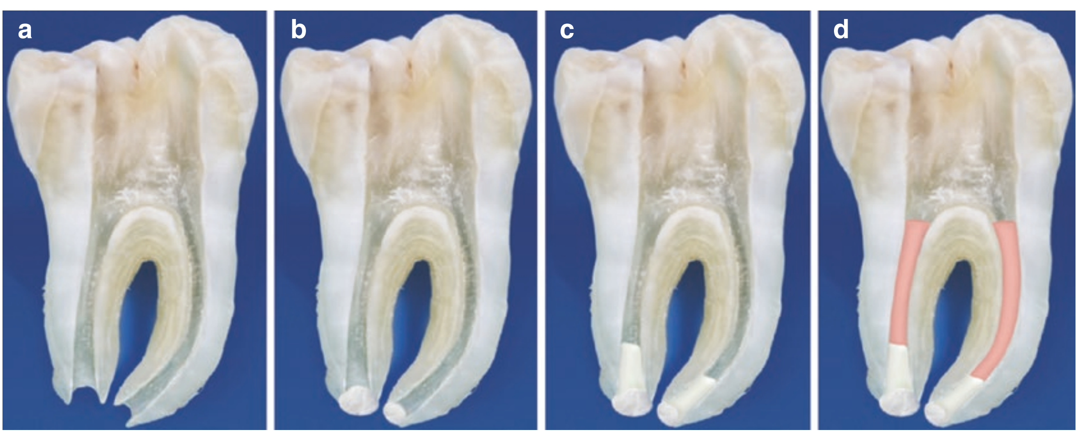

Fig. 6 Two-appointment apexification procedure using Biodentine® or puty-type RRM. At the first visit, open apices (**a**) are isolated with barrier material (**b**), and 4–6 mm of a root repair material as an apical plug is placed (**c**). The remaining root canals are obturated at the second visit with gutta-percha and the sealer (**d**)

empty root canal space can be filled with injectable calcium hydroxide paste, and the temporary filling material should be placed. During the second visit, the tooth is reopened under aseptic conditions, and the root canal obturated with gutta-percha and sealer (Fig. 6d).

The tooth crown should be restored with a permanent restoration. If the entire root canal has obturated with the hydraulic calcium silicate–based material, just endodontic access isolation with a temporary filling material is needed at the first appointment, and the final restoration is placed during the second visit.

As it was mentioned before, to maximize the reinforcement capabilities of the condensable hydraulic calcium silicate–based materials and replace radicular, cervical, and coronal dentine, it was suggested to use Biodentine® or putty-type RRM to fill entire canal of the undeveloped root as well as entire endodontic access [53]. The few superficial millimeters of the set hydraulic calcium silicate–based material can be replaced with composite after 3–6 months during the follow-up appointment [59] (Fig. 7).

Despite the fact that root canals of undeveloped roots usually are very wide, and the apical part of the canal is easily accessible under or sometimes even without magnification, some clinical situations can still be challenging. Those difficulties usually are related to multirooted teeth with significant root curvatures. In these situations, the paste-type root repair materials like iRoot®BP, EndoSequence® BC RRM™, and TotalFill® BC RRM™ Paste can be successfully used in conjunction with injection technique. These materials can be used during the two-visit apexification procedure as an apical 4–6 mm plugs, a subsequentially obturating root canal with gutta-percha and sealer (Fig. 8).

Also, these RRM pastes can be used for the single-visit apexification procedure, when the entire root canal is filled with the paste at the level of the orifices (Fig. 9).

For both techniques, the clinical steps of isolation, cleaning-shaping as well as final crown restoration are identical to these, when putty-type materials are used and were described before.

5 Perforation Repair

Iatrogenic errors, such as root canal transportations, ledging, zipping, and others, can lead to uncontrolled and accidental root perforations. The risk of perforations significantly increases during endodontic retreatment procedures [60, 61]. Visualization of the perforation area is a very important factor leading to the success of the

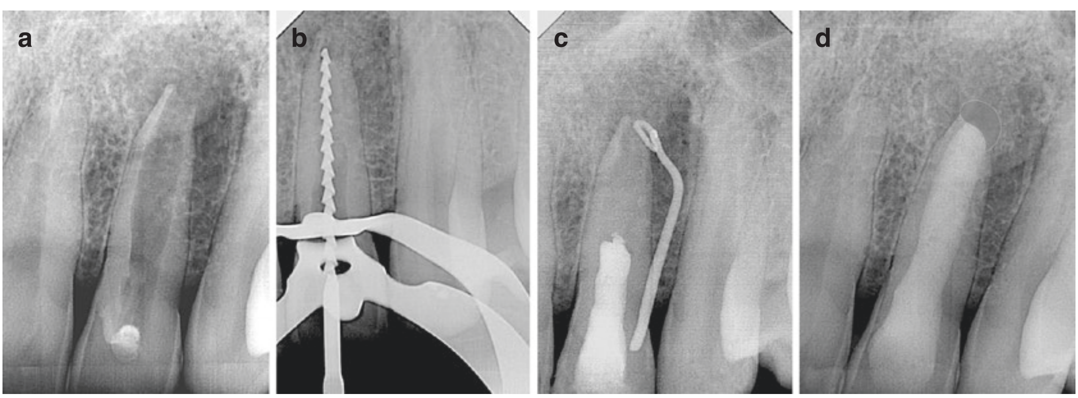

Fig. 7 Apexification of the upper incisor using Biodentine®. The undeveloped root with thin walls and periapical lesion detected on X-ray (**a**). Root canal cleaned-shaped and calcium hydroxide paste placed for 10 days (**b**). The sinus tract was visible at the second visit (**c**); root canal was recleaned and calcium hydroxide paste replaced. No complaints or clinical signs were detected at the third visit; the apical barrier was created using Hemocollagene and root canal, and endo access were filled with Biodentine® (**d**)

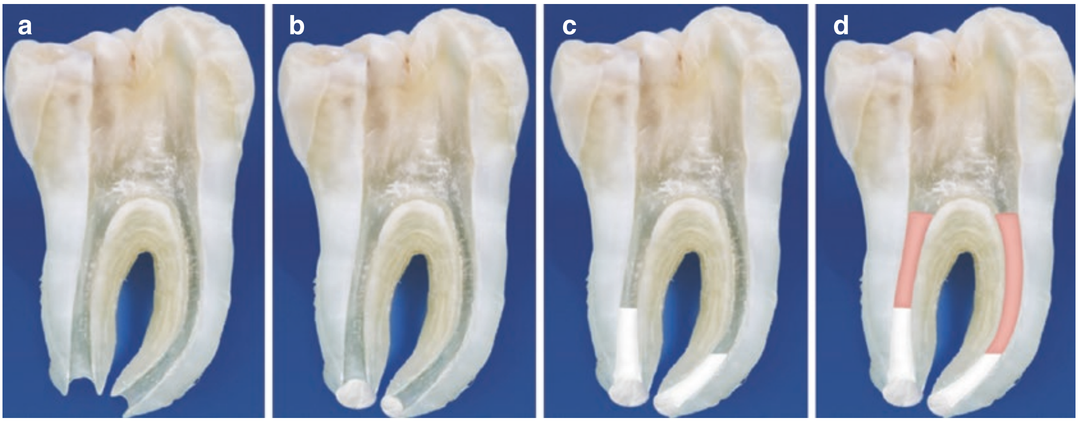

Fig. 8 Two-appointment apexification procedure using injectable RRM paste. At the first visit, open apices (**a**) are isolated with barrier material (**b**), and 4–6 mm of a flowable root repair material as an apical plug is placed (**c**). The remaining root canals are obturated at the second visit with gutta-percha and the sealer (**d**)

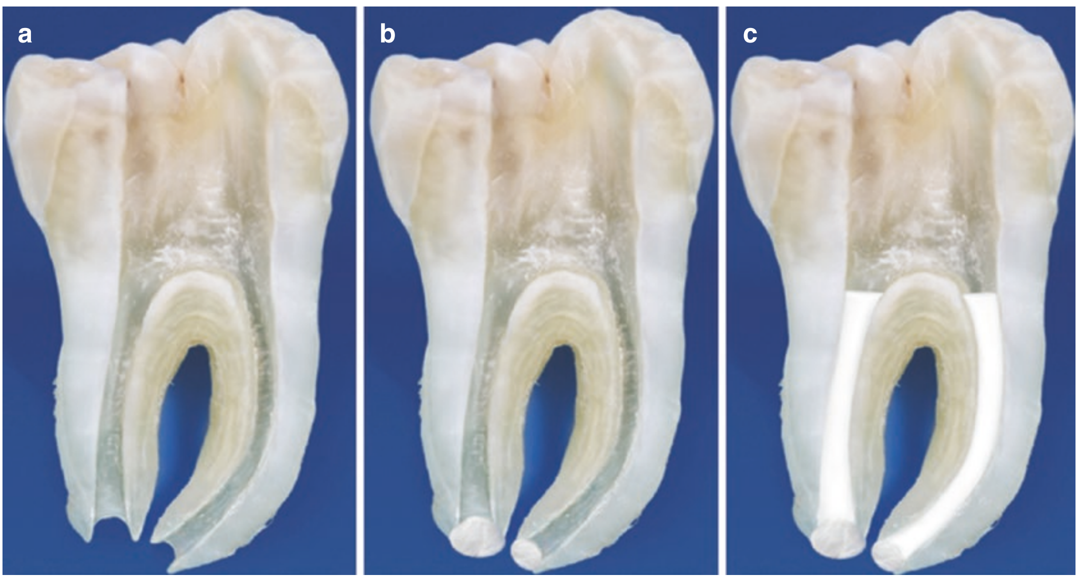

Fig. 9 Single-visit apexification procedure using injectable RRM paste, filling entire canals of undeveloped roots. Open apices (**a**) are isolated with a barrier material (**b**) and entire root canals obturated with a flowable RRM paste (**c**)

treatment; however, direct observation of perforations beyond the curvature of the root canal is limited even if a dental microscope is used [62]. It leads to the complicated delivery of repair material, lack of appropriate control during condensation, and, as a consequence, poor apical seal [63].

5.1 Definition, Etiology, and Clinical Manifestation

Perforations are defined as communication between the root canal system and the periodontal tissues [64]. They can be caused by the pathological process, like caries or resorption, or can be created iatrogenically during endodontic treatment or especially retreatment (zip, strip, furcation perforations) as well as during restoration of endodontically treated teeth (for example, post preparation perforation). It has been shown that 53% of all perforations occur during prosthetic and 47% during endodontic treatment procedures [2]. When perforation occurs, the inflammatory reaction in the periodontal tissues starts and progresses if the perforation is not managed using biocompatible materials [65]. The inflammation is caused by both mechanical trauma with endodontic instruments or burs and extrusion of the debris, microorganisms, and their byproducts to the perforation site [64].

It has been concluded that the perforation should be immediately sealed after identification as delayed sealing is directly related to the worse prognosis or even the loss of the tooth [64]. Sometimes, the treatment of the perforations requires a multidisciplinary approach—nonsurgical and surgical procedures are required. From the clinical point of view, the level, position, size–shape, and time of occurring of the perforation are the most critical factors influencing the treatment approach and outcome [1, 61]. Perforations can occur in all thirds of the root, while the apical and middle-root perforations have a better prognosis in comparison to coronal or furcal perforations [62].

The localization of perforations can be as diverse as possible. They can be located on the buccal or lingual, mesial or distal surfaces of the roots. It has been concluded that the sealing quality mainly depends on the size and shape of the perforation—the bigger size of the perforation, the bigger area of exposed periodontal tissues should be covered and sealed. Usually, the lateral or furcal perforations are oval-shaped or elliptical as they are made with a bur or endodontic instrument crossing the dentin under the angle. However, the cross-sectional configuration and size of apical perforations related to previous transportation, ledging, and over-instrumentation in curved roots are unpredictable [66]. They can vary significantly, depending on the root length, radius, and degree of the curvature (Fig. 10), making the management of these perforations even more complicated.

Apical perforations usually occur as a consequence of inaccurate instrumentation of curved canals, transporting the apical third of the canal and destroying the integrity of the apex. The most crucial aim in this clinical situation is the negoti-

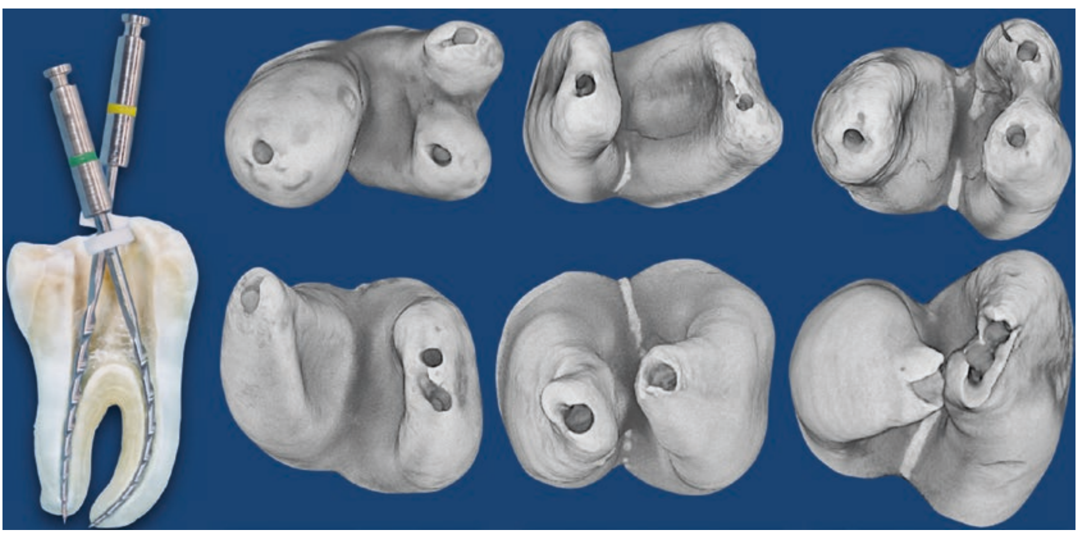

Fig. 10 3D micro-CT reconstructions of the experimentally perforated curved roots of mandibular molars. The cross-sectional diameter and configuration of apical perforations are unpredictable and vary depending on the anatomical features of the roots

ation of the original root canal (using pre-curved hand instruments, copious irrigation, and constant agitation of the irrigants). If the procedure is successful, the original root canal is cleaned, shaped, and obturated, no additional sealing of the perforation is required, especially if it is small, “spot” type perforation. However, this clinical condition is a bit more historical. Nowadays, the majority of the root canals are shaped using engine-driven endodontic instruments. It should be mentioned that if the apex is perforated with a large taper rotary or reciprocating file, the size of the perforation will be much larger than the original size of the instrument. It is related to the significant increase in the diameter of the instrument with every millimeter of its length. If the perforation is made with the same size, but different taper instruments (for example, 0.4, 0.6, 0.7, or 0.8), the perforation diameters will vary significantly. Moreover, the alloy of the instrument is directly related to the perforation size in curved roots, too. All NiTi instruments possess a so-called “shape memory” effect and are trying to straighten in the curved root canals [67]. If perforation occurs and the instrument is rotating beyond the apex, the cross-sectional shape of perforation will become even more oval [68]. Therefore, the CM NiTi instruments do not have any negative straightening effect on the root canals and are less “harmful” if perforations occur [69].

The middle-third perforations usually occur during cleaning and shaping of the canal system or the preparation of a post space using rotary instruments such as Peeso or Largo reamers, Gates Glidden burs, or others [70]. These perforations can occur in all teeth, requiring the metallic or fiber post for crown restoration. To avoid these perforations, the main preoperative factors should be determined before post space preparation: the inclination of the tooth, the individual anatomical features, the curvature and thickness of the root, and the size of the bur [71]. The second type of middle-root perforations is strip perforations, usually occurring on the concave side of the mesial roots of lower or mesiobuccal roots of upper molars [72]. Usually, the excessive amount of the dentin is removed by the operator, due to aggressive instrumentation using rigid stainless steel or big taper endodontic instruments.

Furcal or coronal-third perforations usually occur during endo access preparation in teeth with extensive pulp chamber calcification or different angles of tooth inclination [73]. These perforations can be made by preparing the space for the different types of the post when preoperational risk factors are not considered. The floor of the pulp chamber or coronal-third of the root usually is perforated by the clinician exploring the obliterated orifices of the root canals or losing the anatomical signs. Even the use of the magnification or ultrasonic devices not always guarantee success. If the perforations are not managed immediately, there is an increased risk of the rapid alveolar bone resorption, migration of the epithelium, and periodontal pocket formation [74]. The treatment of these periodontal defects becomes complicated and adversely affects the prognosis and survival of the tooth [75].

The time when perforations occur and when they are sealed is an essential factor for prognostication of the outcome [62]. Perforation causes the inflammatory reaction in the surrounding tissues and prolonged period can cause a substantial breakdown of periodontal tissue, which can complicate the management of old perforations or even cause the tooth loss [74]. It is widely accepted that perforations should be sealed as soon as possible, preferably at the same appointment of their occurrence [64, 75].

5.2 Techniques of the Perforation Repair

The selection of the material to be used for root perforation repair in every clinical situation highly depends on the clinical conditions, such as size and localization of the perforation, the possibility to access the perforation site directly, deliver and manipulate repair material under visual control, and the experience of the operator. If the clinical situation is complicated and not allows the clinician to deliver and condensate cement or putty-type material under appropriate control, it is recommended to use flowable materials. It can be expected that due to the high flowability and penetrability of the hydraulic calcium silicate–based materials, the sealing quality of the difficultly accessible perforation site will be better.

5.2.1 Perforation Repair Using Putty-Type Materials

The Type 5 hydraulic calcium silicate–based root repair materials that are launched as a semi-solid plasticized or putty-type materials are different in their applicability in comparison to MTA cement. These materials are not hard or brittle but rather more plastic [16]. The hydraulic calcium silicate–based root repair materials like a Biodentine® should be mixed before use, while the iRoot®BP Plus, EndoSequence® BC RRM™/TotalFill® BC RRM™ Putty as well as their fast setting formulations iRoot®FS, EndoSequence® BC RRM™/TotalFill® BC RRM™ Fast Set Putty are premixed and can be used without any additional preparation. It has been shown that some condensation of these materials is needed to achieve homogeneous and voids-free fillings [15, 76]. Thus, preferably the clinicians using these materials for the management of perforations should have appropriate direct visual control to deliver and condensate materials at the perforation site. Clinically, these putty-type condensable materials are recommended to be used for management of all perforations: furcation, coronal, middle or apical, and repair procedure by itself is not very different as it is using MTA cement.

For the repair of furcation perforation, the tooth should be isolated with a rubber dam, endo access opened and disinfected with a sodium hypochlorite, perforation sites visualized, and the size identified [17, 72]. It is recommended to use a collagen or hemostatic material barrier matrix to control bleeding and exudation and prevent the extrusion of repair material into periodontal tissues [75]. The additional attention should be paid to the old perforations, as these are often associated with the bone resorption in the furcation area [74]. Subsequentially, more barrier material can be required to create an adequate matrix in the resorbed bone. Finally, the pulp chamber is gently dried with a dry cotton pellet, and preferable hydraulic calcium silicate–based material is dispensed and condensed in small increments until the perforation is repaired (Fig. 11). Perforation repair and crown restoration can be performed in a single step if fast setting materials are used.

If the root perforation, which can be visualized and well accessed using magnification, repair using putty-type materials is performed, the tooth is isolated with a rubber dam, endo access opened and disinfected, the perforation site is accessed, and size of perforation is identified. Thereafter, the root canal cleaning-shaping procedures should be done in a conventional manner avoiding over-instrumentation or extrusion of irrigants beyond perforation [77]. A root canal should be dried and can be filled with antibacterial dressing material (for example, calcium hydroxide or bioceramic-based paste) for disinfection between visits. If temporary dressing is used, the endo access should be isolated with an intermediate restorative material. At the next visit, the tooth is isolated, endo access reopened, root canal recleaned, dried, and preferable putty-type hydraulic calcium silicate–based material is dispensed over the perforation site using a suitable instrument and condensed with a plugger. The excess material should be removed, root canal filled with calcium hydroxide/bioceramic-based paste and a temporary filling placed. The root canal treatment should be completed at the next visit according to the current recommendations [17].

5.2.2 Perforation Repair Using Flowable Materials and Injection Technique

The direct visualization of the perforation site and control of repair procedures have an important impact on the outcome of the perforation repair [62]. Even if the handling characteristics and clinical applicability of the new fourth and fifth type hydraulic calcium silicate–based putty-type materials are superior to MTA, some clinical challenges still exist. It should be mentioned that even under magnification, the repair

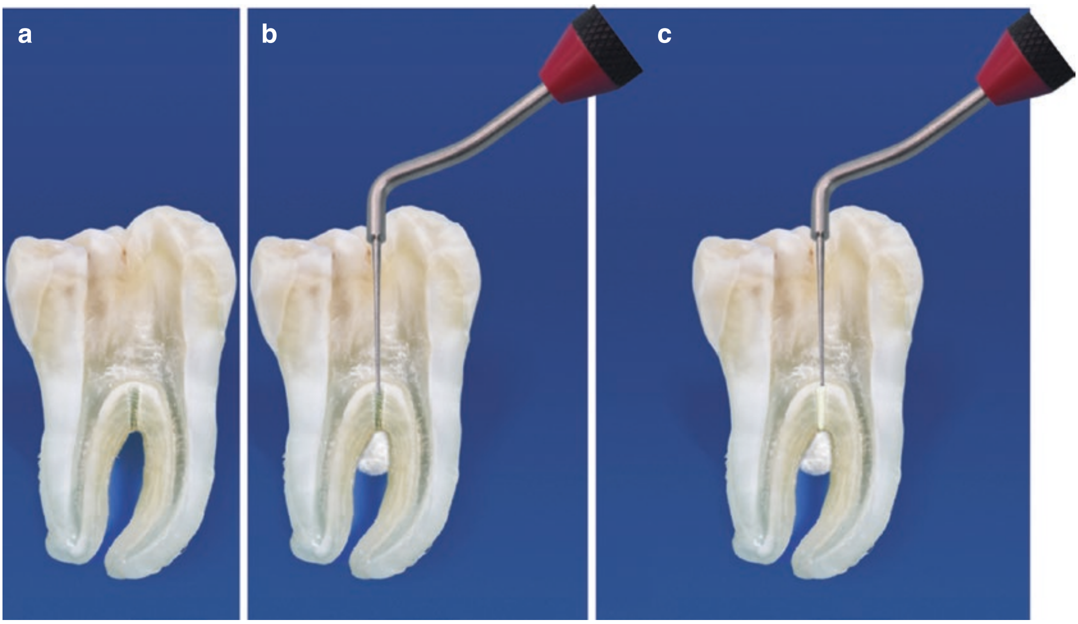

Fig. 11 Furcation perforation of mandibular molar (**a**). The matrix-barrier is created using collagen-based material delivered into the furcation area using pre-fitted plugger, smaller than perforation diameter (**b**). The putty-type hydraulic calcium silicate–based material is delivering to the perforation in small increments and condensed against matrix (**c**)

of the root perforations that are localized in a difficultly accessible sites (for example, apical perforation in curved roots) with a limited direct visibility, the flowable paste-type root repair materials can be superior in comparison to condensable putty-type materials. Another clinical situation, when these paste-type materials can be superior over the condensable hydraulic calcium silicate-–based materials are small furcation perforations or perforations in narrow root canals when material delivery even using smallest plugger is not convenient or possible. Moreover, it has been shown that the smaller perforation, the fewer chances that significant bone resorption, and periodontal tissue breakdown will occur [61, 62]. Therefore, the matrix or barrier in case of the small perforation is usually not needed, as the periapical tissue pressure is sufficient to protect from the extrusion of the repair material, especially non-condensable [70, 78] (Fig. 12). If injectable root perforation repair is selected, all clinical steps and procedures before delivering the materials are the same, as described previously.

5.2.3 Perforation Repair Using Single-Cone or Modified Single-Cone Obturation Techniques

The performance of flowable hydraulic calcium silicate-–based root repair pastes, as perforation repair materials, is well investigated [11, 15]. However, these materials are quite expensive and often not available in the daily general dental practice. It has been shown that majority of endodontic complications are treated by endodontists instead of general practitioners [79, 80]. However, the root canal obturation using hydraulic calcium silicate–based sealers and single-cone obturation technique is gaining popularity among general dentists [81]. It can be expected that they are familiar with the properties of these sealers and clinical applicability.

Recently. it has been claimed that hydraulic calcium silicate–based sealers such as BioRoot™ RCS, EndoSequence® BC Sealer™, and TotalFill® BC Sealer™ can be used not only as sealers but also as injectable biological fillers, too [82, 83]. Main properties of these materials such

Fig. 12 Small diameter furcation perforation (**a**) can be repaired using injectable root repair material (**b**)

as antimicrobial activity, biocompatibility, and bioactivity are identical to root repair formulations [84]. Thus, these materials can be used as biological fillers in clinical situations, when significant root repair–dentine replacement or root reinforcement is not needed, and when the perforation and communication of the root canal space and periodontal tissues is not extensive [33]. These clinical situations can be an accidental apical root canal transportations and perforations, lateral or strip root perforations, with a limited or difficult accessibility and lack of direct visual control [78].

When the strip or lateral perforation is localized in the middle-apical thirds at the level of the root curve or beyond, but the integrity of the apical constriction is not damaged, there is a possibility to repair existing perforations without any specific repair manipulations or procedures. After root canal debridement using copious irrigation with appropriate irrigants and irrigation techniques, canals of perforated roots should be dried and master gutta-percha point pre-fitted. Afterwards, the root canal is filled with flowable hydraulic calcium silicate–based sealer, which in these clinical situations are used as a biological filler, and gutta-percha point is reinserted to the full working length. The superior flowability of the materials and additional hydraulic pressure inside root canal can ensure distribution and penetration of the sealer-filler into the "false canal" and seal the perforation without any additional manipulations (Fig. 13).

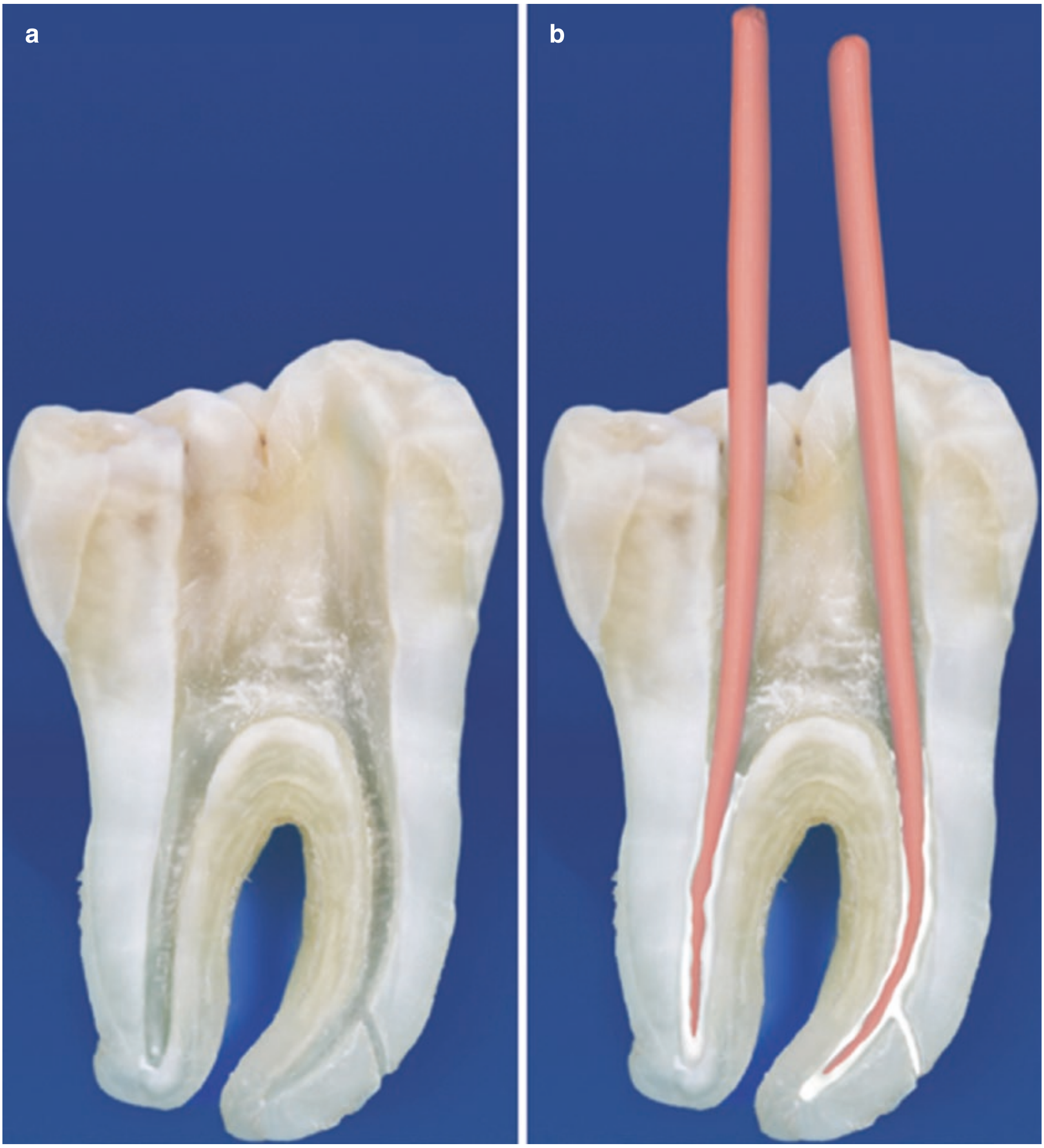

Fig. 13 Small lateral root perforations (**a**) can be managed without any specific treatment procedures, if flowable hydraulic calcium silicate-–based material and single-cone technique are used for obturation; high flowability and penetrability of the material can ensure acceptable results (**b**)

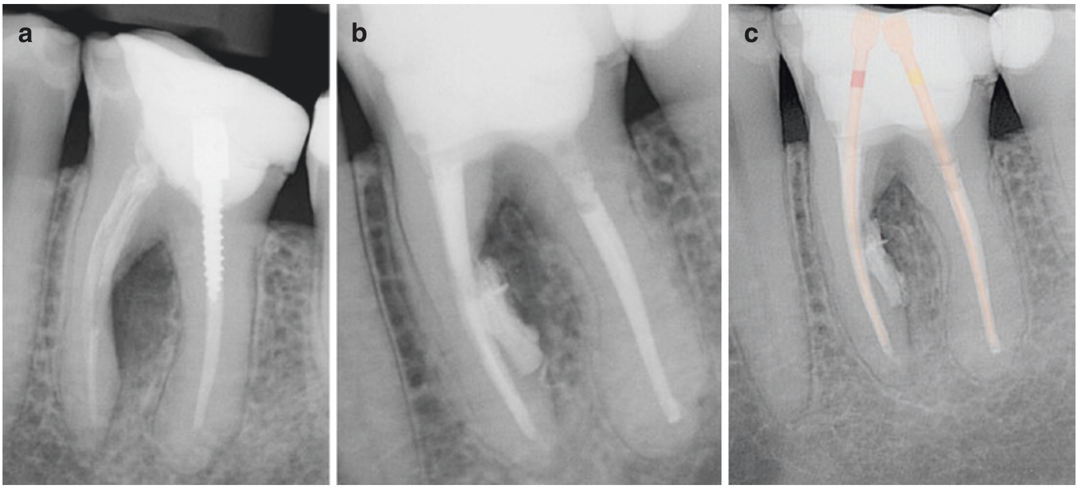

Fig. 14 Management of the strip perforation of the tooth 36, using a modified single-cone obturation technique. Preoperative radiograph shows strip perforation of the mesial root and extensive lesion in the furcation area (**a**). Endodontic retreatment performed using conventional cleaning and shaping protocol and 1-week calcium hydroxide therapy; root canals were obturated with BioRoot™ RCS sealer and single gutta-percha cone (**b**). No clinical symptoms and noticeable healing of the lesion 12 months after endodontic retreatment (**c**)

The single-cone root canal obturation technique can be used by general practitioners for the management of some endodontic complications with acceptable clinical results (Fig. 14). Despite some evidence of success, more clinical investigations are needed to confirm the clinical efficiency of these simplified techniques.

However, if the integrity of the apical constriction is affected, the standard single-cone technique in conjunction with hydraulic calcium silicate–based sealers–fillers should be modified. Using the modified single-cone obturation technique, the master gutta-percha point is selected, pre-fitted at the full working length with a tug-back effect, and cut 2–3 mm shorter than the working length with a sterile scalpel. When hydraulic calcium silicate–based flowable material is delivered into the root canal, and gutta-percha point is reinserted, the apical 2–3 mm are filled with antibacterial, biocompatible, and bioactive material, which comes into direct contact with periodontal tissues (Fig. 15). The gutta-percha point helps to improve the sealer–filler distribution into root canal space and all irregularities. This modified technique can be clinically appealing because it does not require superior handling skills of the clinician nor the direct visual control of the procedure.

It has been shown that this technique can ensure tight, homogeneous, and minimally porous filling of the apical third of perforated curved roots of mandibular molars (Fig. 16) [58].

6 Repair of Resorptive Defects

The etiology of external and internal tooth resorption is multifactorial [85, 86]. They can be caused by pulp necrosis, dental trauma, orthodontic treatment, professional hygiene procedures, or tooth whitening [87, 88]. The treatment modalities significantly depend on the type and localization of the resorption [89]. While small defects of the apical external resorption can be just monitored or internal root resorption usually is not difficult to manage and repair, and the extensive external cervical resorption can be extremely challenging for the clinicians.

Calcium hydroxide as a material of choice for treatment of different resorptions was used until the MTA was introduced for resorption repair [90, 91]. However, previously mentioned drawbacks of these materials, made the hydraulic

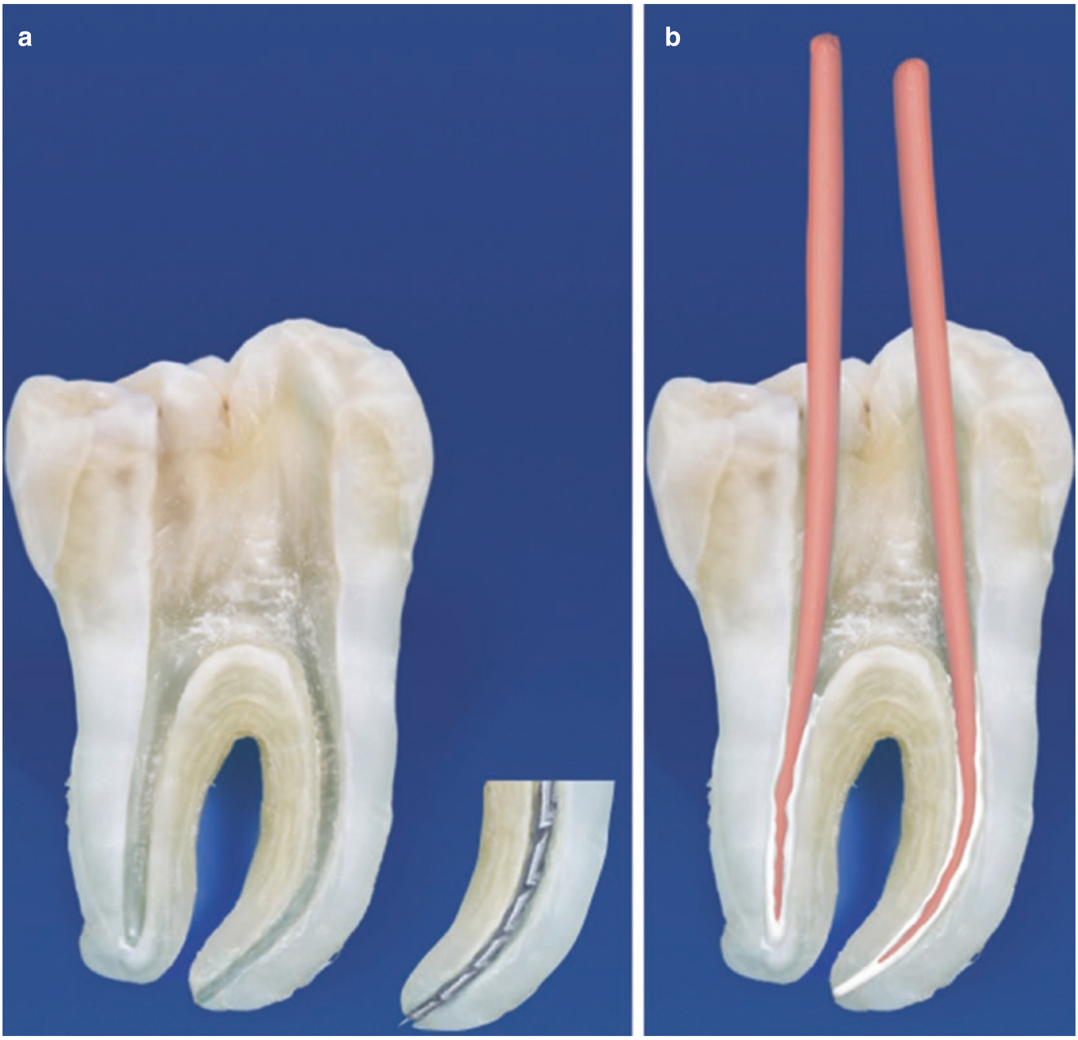

Fig. 15 If accidental apical root perforation is made with a smaller endodontic instrument (**a**), the modified single-cone obturation technique with hydraulic calcium silicate–based sealer-filler can be used for repair (**b**)

calcium silicates very popular for the management of external and internal resorption [15, 92]. Depending on the type of resorptions, they can be repaired using flowable and solid hydraulic calcium silicate–based materials. External apical inflammatory, internal or internal-perforating resorptions can be repaired using all available materials (Fig. 17). While external cervical resorptions preferably should be repaired using fast set type materials, to avoid possible wash out of the material [15, 93, 94].

It has been shown that apical periodontitis with a periapical lesion is very often associated with an extensive external apical inflammatory root resorption, which usually is not visible on conventional radiographs [95, 96]. The resorption usually progresses from the tip of the root towards apical constriction, and after some time crater-type defect on the tip of the root is established, and natural apical stop is disrupted. These resorbed root tips look like undeveloped roots or roots with extensive apical root perforation. If conventional root canal obturation technique with pre-fitted master gutta-percha point is selected, despite the tug-back effect was achieved, there is a risk that some resorbed areas will not be

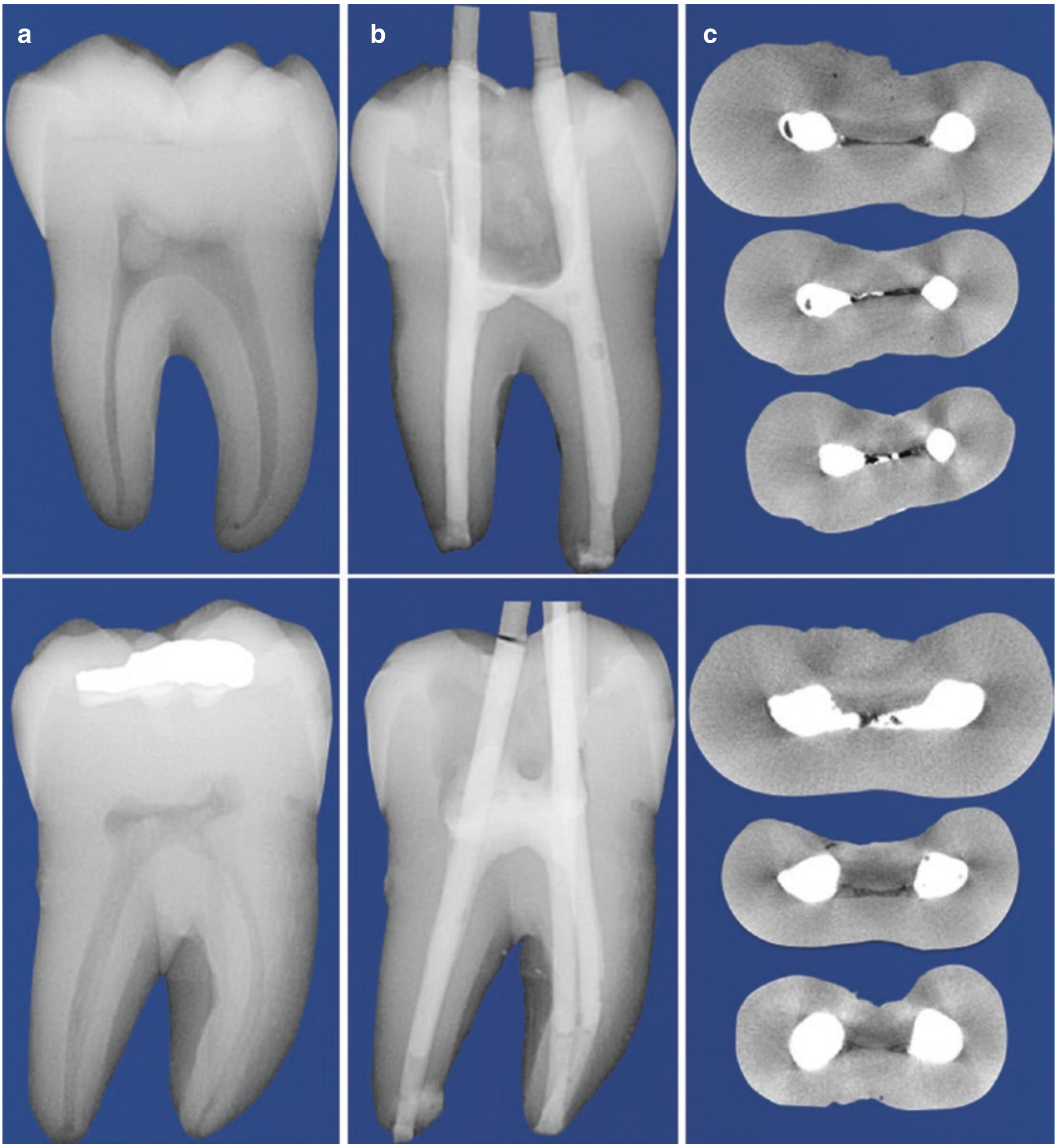

Fig. 16 Mandibular molars before experimental apical perforation of the curved roots (**a**). X-rays of the teeth, after filling of apical perforations root canals with BioRoot™ RCS as a filler and in conjunction with single gutta-percha point, using modified obturation technique (**b**). The cross-sectional images of micro-CT scan at coronal, middle, and apical thirds of the roots (*top to bottom*), demonstrating the homogeneity of the fillings (**c**)

hermetically sealed (Fig. 18). Thus, the clinicians can face a serious problem, which is not detectable neither clinically nor radiographically.

In this case, the injectable hydraulic calcium silicate–based root repair material or previously described modified single-cone obturation technique with a sealer-filler can be used, to fill 1–2 mm of the apical root canal with a hydraulic calcium silicate–based material.

Non-perforating or perforating internal root resorptions can be repaired using a wide range of Type 4 or Type 5 hydraulic calcium silicate–based materials [15]. The treatment preferably should be performed under profound anesthesia and a rubber dam isolation. The root canal should be accessed in a conventional way, while a cleaning and shaping procedures should be accompanied with a copious root canal irrigation with a solution of sodium hypochlorite agitated using sonic or ultrasonic agitation techniques [97]. The root canal and resorption defect should be dried with paper points and filled with calcium hydroxide or temporary bioceramic paste for disinfection between visits. It is recommended to use premixed pastes as these materials are easier to inject into the root canal and fill resorption defect due to the increased flowability of these materials [98]. Meanwhile, the removal of these premixed pastes is easier in comparison to *ex tempore* mixed paste, due to the additives decreasing the adhesion of the materials to the dentin [99]. Afterwards, the access cavity should be filled with temporary cement to protect the temporary root canal filling. At the next visit (usually after

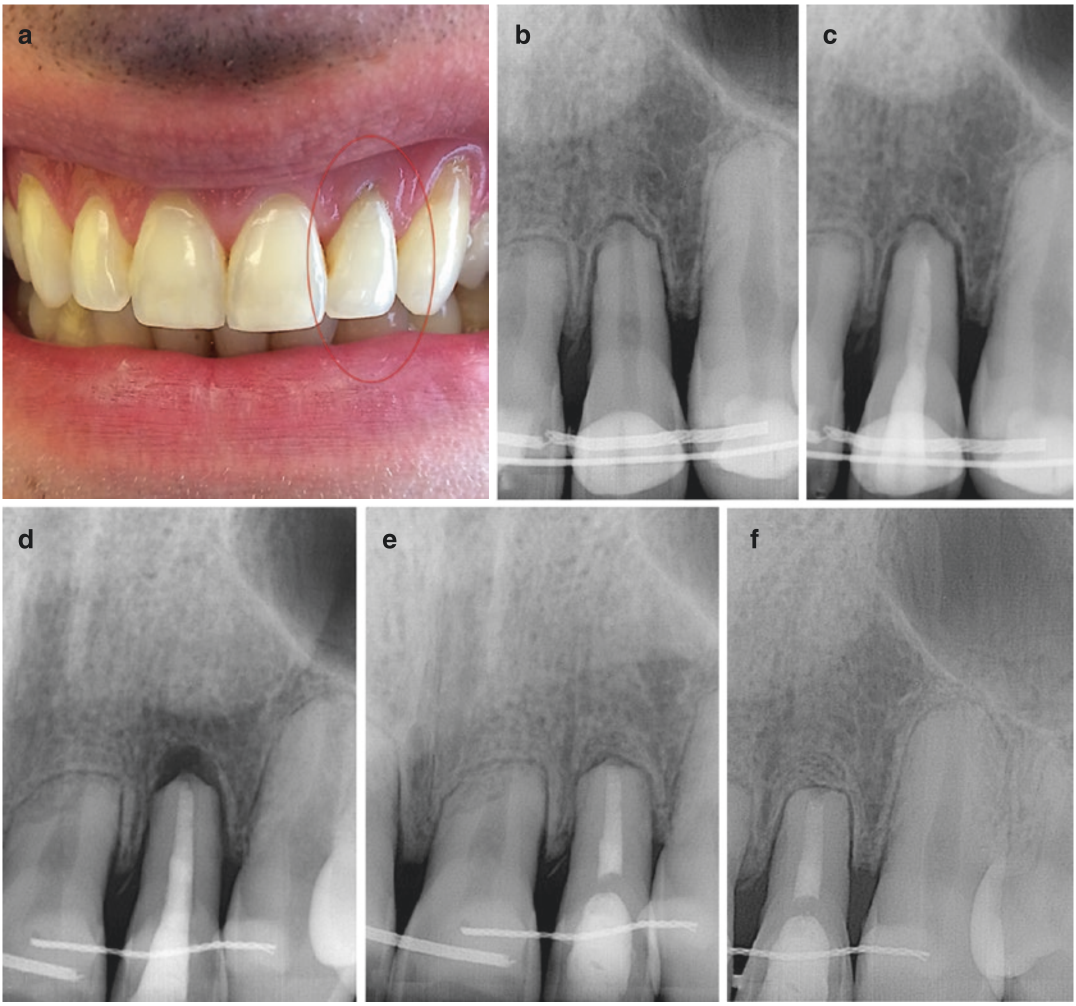

Fig. 17 Clinical (**a**) and radiographic (**b**) view of the tooth 22 2 weeks after trauma. Mild sensitivity on the bitewing and percussion, no reaction to thermal tests were detected. Extensive generalized root resorption after orthodontic treatment was visible. Conventional cleaning and shaping were performed, and premixed calcium hydroxide paste was placed for 1-week (**c**), and replaced for additional 2 weeks, due to some mild discomfort on bitewing and increased periapical radiolucency on the follow-up X-ray (**d**). The tooth was asymptomatic after 2 weeks; the entire root canal was filled with Biodentine®, using Hemocollagene as an apical matrix (**e**). No clinical symptoms or visible changes on X-ray were detected after 6 months follow-up (**f**)

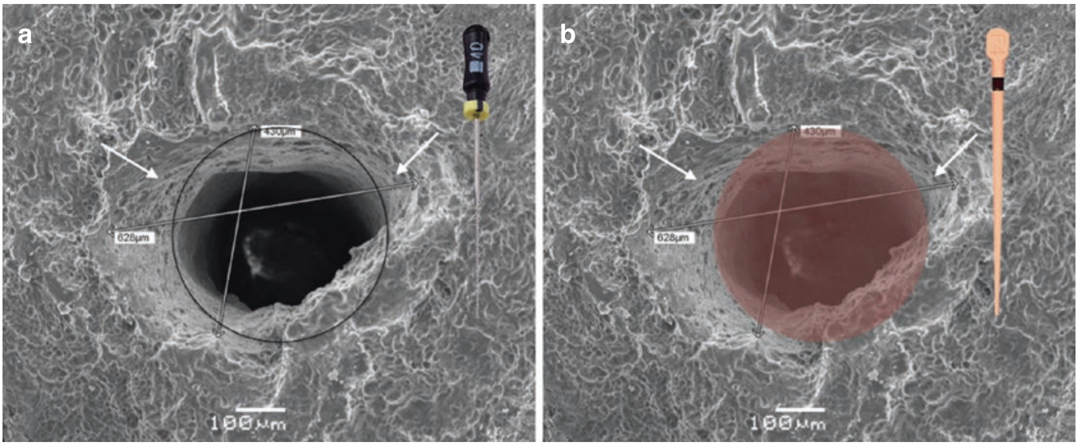

Fig. 18 SEM images of the surface of the tip of the medial root of the mandibular molar, affected by chronic apical periodontitis associated with the periapical lesion. Crater-type external resorption disrupted the integrity of apical constriction, while the root canal cross-sectional configuration is not uniform. If root canal will be enlarged up to file #40 (**a**) and the same size master gutta-percha point will be pre-fitted with a tug-back effect at the full WL (**b**), some resorbed areas—irregularities—(*white rows*) will be filled just with sealer, which potentially can be resorbed, compromising the tight apical seal over the time

1 week), a rubber dam should be placed, the temporary restoration removed, calcium hydroxide or bioceramic paste flushed out using citric acid [100], and root canal recleaned in the same manner as the first visit. Subsequentially, root canal/resorption defect is dried with paper points and filled with the preferable material. If plasticized materials like a Biodentine®, iRoot®BP Plus, EndoSequence® BC RRM™, and TotalFill® BC RRM™ Putty are used, the root canal below the resorption defect is obturated using gutta-percha and sealer. Subsequently, repair materials are delivered over the resorptive defect using a suitable instrument and gently condensed with a plugger. Meanwhile, if the paste-type materials are used, the entire root canal and resorption defect can be filled by injecting these materials. After the filling of the root canal and resorption defect, the X-ray to check that the material is correctly positioned should be taken (Fig. 19). Finally, the temporary filling or permanent restoration should be placed, depending on the clinical situation.

Aggressive and extensive external cervical root resorptions are challenging when they cause significant root damage [85]. However, when extensive resorption defect results in pulpits and subsequently infection of the resorption defect, the endodontic treatment of the tooth in conjunction with surgical repair of the root is the only viable option to save a tooth [101]. However, if external cervical resorption is extensive, the extraction of the tooth can be the only treatment of choice [86]. In cases when direct surgical access with good visualization of the resorption defect can be achieved, the use of fourth or fifth type of hydraulic calcium silicate–based repair materials, which are easy to apply to the site and have demonstrated excellent biocompatibility, bonding, and hydrophilic qualities, nowadays should be the first clinical choice. It has been shown that the use of nanoparticulate premixed fast setting putty formulations can be superior due to decreased risks to be washed out [94]. Long-term follow-up of the healing of the compromised clinical cases of external cervical resorption repair revealed good periodontal tissues healing, acceptable esthetics, and a lack of dentin staining [101, 102].

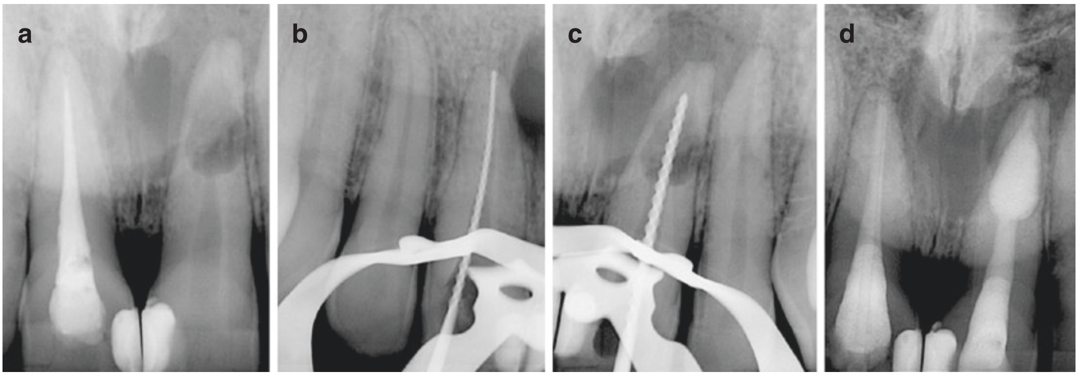

Fig. 19 The perforating internal resorption and lesion of the surrounding tissues of the tooth 21 and apical periodontitis of the tooth 11 (**a**). Endodontic retreatment for tooth 11 and treatment for tooth 21 performed using conventional cleaning and shaping protocol and 1-week calcium hydroxide therapy (**b**, **c**). The root canal of the tooth 11 was obturated with BioRoot™ RCS sealer in conjunction with a big taper single gutta-percha point; the root canal and resorption defect of the tooth 21 were filled with a TotalFill® BC RRM™ Paste (**d**)

7 Endodontic Surgery Procedures

When endodontic treatment is not successful, and nonsurgical endodontic retreatment fails or is not possible, the endodontic surgery is indicated [103]. However, due to the rapid developments in implant dentistry, the endodontic surgery is becoming less popular in comparison to the tooth replacement with an implant. It should be mentioned that some clinical investigations detected better prognosis of the dental implant in comparison to retreatment procedure; however, well-designed clinical trials demonstrated the opposite—the endodontic retreatment is equally effective treatment option, if not superior [104].

The MTA was a material of choice as a retrograde filling with high clinical success rates [105]. However, due to the drawbacks of MTA, mentioned before, the Type 4 and 5 hydraulic calcium silicate–based root repair materials have become more and more popular and widespread use in endodontic surgery [13, 106]. The current scientific findings indicate that these materials possess superior properties and handling characteristic and provide similar healing rates after endodontic surgery as MTA cement [107, 108] (Fig. 20).

After the exposure and apicoectomy, the 3–5 mm-depth retrograde cavity should be prepared with appropriate ultrasonic tip, keeping the alignment with the long axis of the root, following the direction and the outline contour of the root canal [109, 110]. The retrograde filling material should be prepared and delivered to the cavity using appropriate instruments, such as Lucas curette (Hu-Friedy Mfg. Co., Chicago, IL, USA), MAP System (Produits Dentaires SA, Vevey, Switzerland), or Dovgan applicator (Vista Dental Products, Racine, WI, USA). A biocompatible and bioactive hydraulic calcium silicate–based material is used to create a stable hermetic seal that can prevent the percolation of bacteria or their products between root canal system and periradicular tissues and promote the healing of these tissues. To prevent the washout of the hydraulic calcium silicate–based retrograde materials, the fast setting formulations such as Biodentine®, iRoot®FS, EndoSequence® BC RRM™, and TotalFill® BC RRM™ Fast Set Putty can be superior to the slow setting putty-type materials [111] (Fig. 21). However, if original formulations are used, the surgical wound should not be irrigated, since this can result in dislodgement of the material. The excess of retro filler should be gently removed with a wet sterile cotton gauze before flap reposition and placement of the sutures.

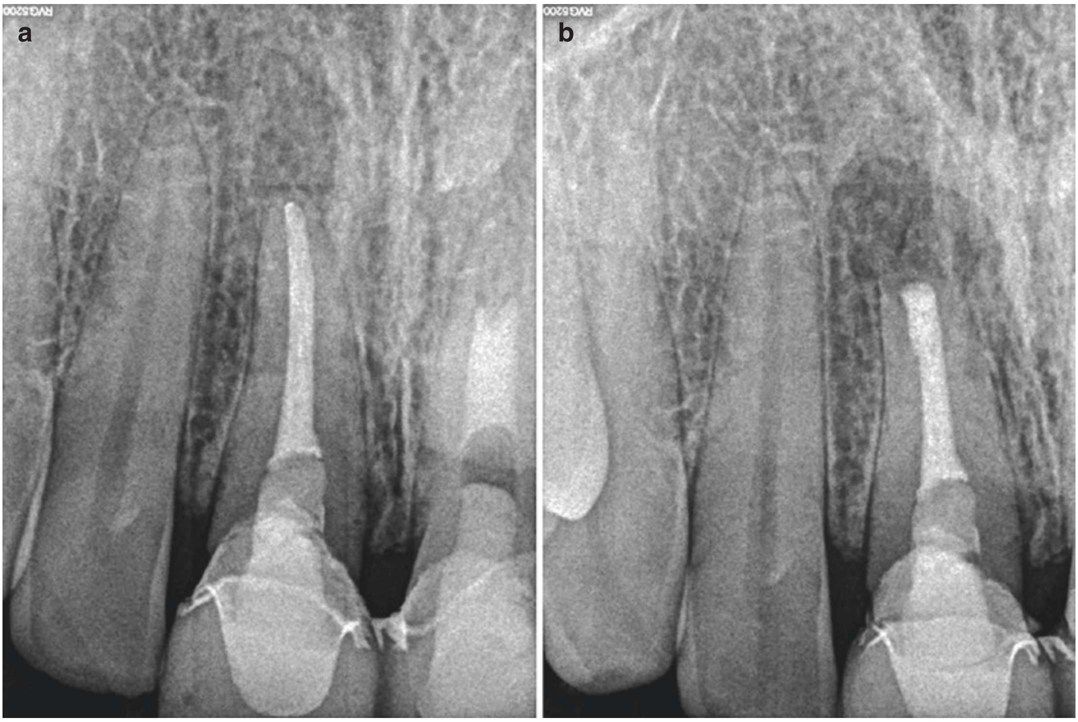

Fig. 20 The successful surgical management of non-healing apical periodontitis. After retreatment and placement of the crown, the clinical and radiographic signs of symptomatic apical periodontitis recovered (**a**). After apicoectomy, root-end preparation was performed using ultrasonic tips, and the retrograde cavity was filled with a TotalFill® BC RRM™ Fast Set Putty (**b**). (*Courtesy Antanas Blazys, DDS*)

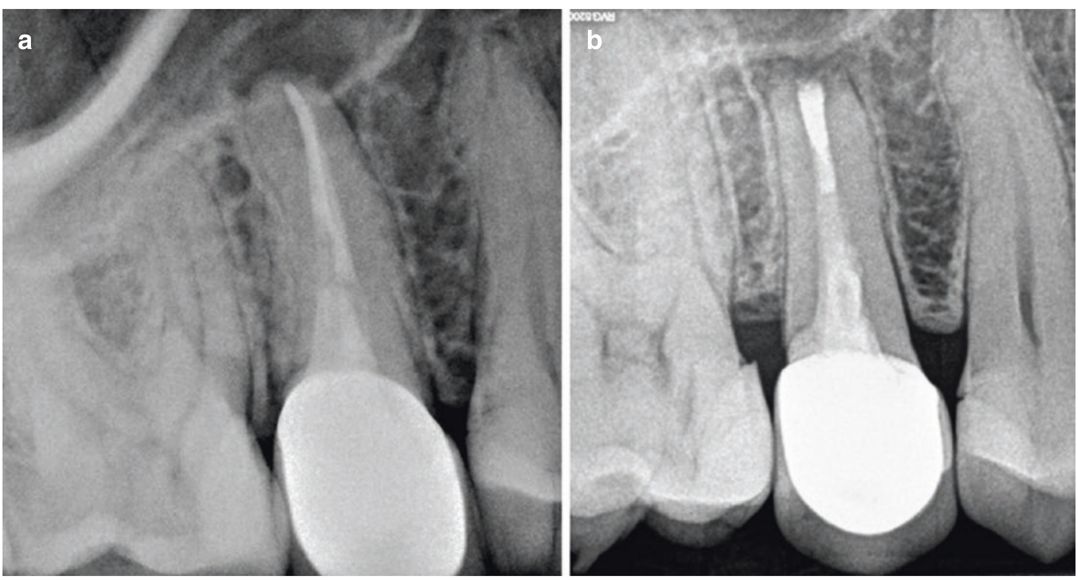

Fig. 21 The clinical symptoms and radiographic signs of apical periodontitis 3 years after endodontic-prosthetic treatment were detected at the day of the patient's visit (**a**). Endodontic surgery was performed, filling the retrograde cavity with a TotalFill® BC RRM™ Fast Set Putty (**b**). CBCT evaluation before surgical intervention revealed the poor quality of primary endodontic treatment and large periapical lesion (**c**–**f**). (*Courtesy Antanas Blazys, DDS*)

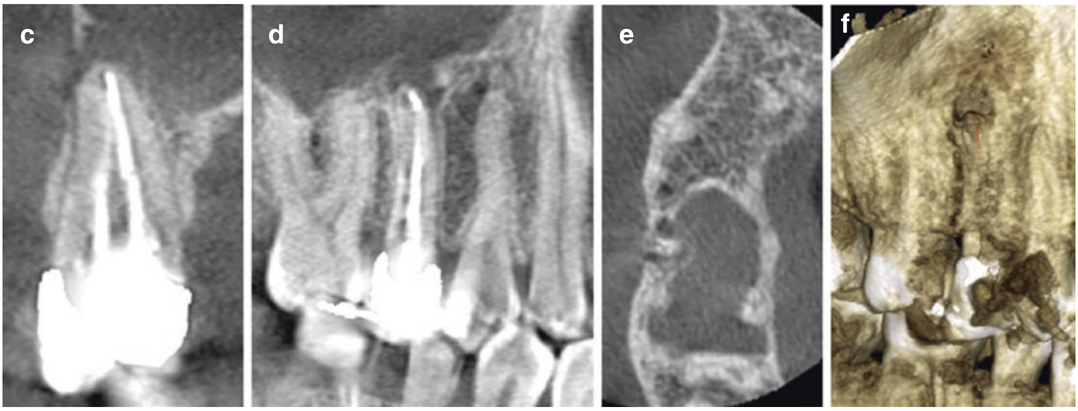

Fig. 21 (continued)

8 Conclusions

Many years ago, MTA has changed existing standards in the management of endodontic complications, vital pulp therapy, or regenerative endodontic procedures. However, the drawbacks of the MTA discussed in this chapter made the use of this material challenging for many clinicians. Recently, the Types 4 and 5 of commercially available hydraulic calcium silicate–based materials have superceded the original MTA and similar formulations as materials of choice for the management of endodontic complications. Nowadays, plasticized, putty-type or paste-type repair hydraulic calcium silicate–based materials are widely researched, and the clinical effectiveness, as well as advantages over Portland cement formulations, are confirmed. The solid scientific background indicates that the newer types of hydraulic calcium silicate–based materials can replace MTA and are the future materials for the management of endodontic complications.

References

1. Siew K, Lee AHC, Cheung GSP. Treatment outcome of repaired root perforation: a systematic review and meta-analysis. J Endod. 2015;41:1795. https://doi.org/10.1016/j.joen.2015.07.007.
2. Clauder T, Shin S-J. Repair of perforations with MTA: clinical applications and mechanisms of action. Endod Top. 2006;15:32. https://doi.org/10.1111/j.1601-1546.2009.00242.x.
3. Parirokh M, Torabinejad M, Dummer PMH. Mineral trioxide aggregate and other bioactive endodontic cements: an updated overview - Part I: vital pulp therapy. Int Endod J. 2018;51:177. https://doi.org/10.1111/iej.12841.
4. Ha W, Kahler B, Walsh LJ. Classification and nomenclature of commercial hygroscopic dental cements. Eur Endod J. 2017;2:27.
5. Khalil I, Naaman A, Camilleri J. Properties of tricalcium silicate sealers. J Endod. 2016;42:1529–35.
6. Silva Almeida LH, Moraes RR, Morgental RD, Pappen FG. Are premixed calcium silicate–based endodontic sealers comparable to conventional materials? A systematic review of in vitro studies. J Endod. 2017;43:527. https://doi.org/10.1016/j.joen.2016.11.01.
7. Jeong JW, DeGraft-Johnson A, Dorn SO, Di Fiore PM. Dentinal tubule penetration of a calcium silicate–based root canal sealer with different obturation methods. J Endod. 2017;43:633–7.
8. Komabayashi T, Colmenar D, Cvach N, Bhat A, Primus C, Imai Y. Comprehensive review of current endodontic sealers. Dent Mater J. 2020; https://doi.org/10.4012/dmj.2019-288.
9. Primus CM, Tay FR, Niu L-N. Bioactive tri/dicalcium silicate cements for treatment of pulpal and periapical tissues. Acta Biomater. 2019;96:35. https://doi.org/10.1016/j.actbio.2019.05.050.
10. Jiang Y, Zheng Q, Zhou X, Gao Y, Huang D. A comparative study on root canal repair materials: a cytocompatibility assessment in L929 and MG63 cells. ScientificWorldJournal. 2014;2014:463826. https://doi.org/10.1155/2014/463826.
11. Zamparini F, Siboni F, Prati C, Taddei P, Gandolfi MG. Properties of calcium silicate-monobasic calcium phosphate materials for endodontics containing tantalum pentoxide and zirconium oxide. Clin Oral Investig. 2019;23:445–57.
12. De-Deus G, Canabarro A, Alves GG, Marins JR, Linhares ABR, Granjeiro JM. Cytocompatibility

of the ready-to-use bioceramic putty repair cement iRoot BP Plus with primary human osteoblasts. Int Endod J. 2012;45:508. https://doi.org/10.1111/j.1365-2591.2011.02003.x.
13. Tran D, He J, Glickman GN, Woodmansey KF. Comparative analysis of calcium silicate-based root filling materials using an open apex model. J Endod. 2016;42:654–8.
14. Lertmalapong P, Jantarat J, Srisatjaluk RL, Komoltri C. Bacterial leakage and marginal adaptation of various bioceramics as apical plug in open apex model. J Investig Clin Dent. 2019;10:e12371. https://doi.org/10.1111/jicd.12371.
15. Debelian G, Trope M. The use of premixed bioceramic materials in endodontics. G Ital Endod. 2016;30:70. https://doi.org/10.1016/j.gien.2016.09.001.
16. Wang Z. Bioceramic materials in endodontics. Endod Top. 2015;32:3–30.
17. Ree M, Schwartz R. Clinical applications of premixed bioceramic materials in endodontics. Endod Pract. 2015;9:111–27.
18. Xu HHK, Carey LE, Simon CG, Takagi S, Chow LC. Premixed calcium phosphate cements: synthesis, physical properties, and cell cytotoxicity. Dent Mater. 2007;23:433–41.
19. Boyadzhieva E, Dimitrova S, Filipov I, Zagorchev P. Setting time and solubility of premixed bioceramic root canal sealer when applicated with warm gutta percha obturation techniques. IOSR J Dent Med Sci. 2017;16:125–9.
20. Guo Y, Du T, Li H, Shen Y, Mobuchon C, Hieawy A, et al. Physical properties and hydration behavior of a fast-setting bioceramic endodontic material. BMC Oral Health. 2016;16:23. https://doi.org/10.1186/s12903-016-0184-1.
21. Abu Zeid ST, Alamoudi RA, Abou Neel EA, Mokeem Saleh AA. Morphological and spectroscopic study of an apatite layer induced by fast-set versus regular-set EndoSequence root repair materials. Materials (Basel). 2019;12:3678. https://doi.org/10.3390/ma12223678.
22. Lagisetti A, Hegde P, Hegde M. Evaluation of bioceramics and zirconia-reinforced glass ionomer cement in repair of furcation perforations: an in vitro study. J Conserv Dent. 2018;21:184. https://doi.org/10.4103/JCD.JCD_397_16.
23. Luo T, Liu J, Sun Y, Shen Y, Zou L. Cytocompatibility of Biodentine and iRoot FS with human periodontal ligament cells: an *in vitro* study. Int Endod J. 2018;51:779. https://doi.org/10.1111/iej.12889.
24. Tian J, Zhang Y, Lai Z, Li M, Huang Y, Jiang H, et al. Ion release, microstructural, and biological properties of iRoot BP Plus and ProRoot MTA exposed to an acidic environment. J Endod. 2017;43:163–8.
25. Reszka P, Nowicka A, Lipski M, Dura W, Droździk A, Woźniak K. A Comparative chemical study of calcium silicate-containing and epoxy resin-based root canal sealers. Biomed Res Int. 2016;2016:9808432. https://doi.org/10.1155/2016/9808432.
26. Olcay K, Taşli PN, Güven EP, Ülker GMY, Öğüt EE, Çiftçioğlu E, et al. Effect of a novel bioceramic root canal sealer on the angiogenesis-enhancing potential of assorted human odontogenic stem cells compared with principal tricalcium silicate-based cements. J Appl Oral Sci. 2020;28:e20190215. https://doi.org/10.1590/1678-7757-2019-0215.
27. Tibau AV, Grube BD, Velez BJ, Vega VM, Mutter J. Titanium exposure and human health. Oral Sci Int. 2019;16:15. https://doi.org/10.1002/osi2.1001.
28. Camilleri J. Biodentine™ The dentine in a capsule or more? https://www.septodontcorp.com/wp-content/uploads/2018/02/Biodentine-Article-0118-LOW.pdf. Accessed 31 May 2020.
29. Grech L, Mallia B, Camilleri J. Investigation of the physical properties of tricalcium silicate cement-based root-end filling materials. Dent Mater. 2013;29:e20. https://doi.org/10.1016/j.dental.2012.11.007.
30. https://www.septodontcorp.com/files/pdf/ABS-Technology-Brochure.pdf. Accessed 31 May 2020.
31. https://www.septodontusa.com/products/biodentine. Accessed 31 May 2020.
32. Camilleri J, Kralj P, Veber M, Sinagra E. Characterization and analyses of acid-extractable and leached trace elements in dental cements. Int Endod J. 2012;45:737. https://doi.org/10.1111/j.1365-2591.2012.02027.x.
33. Simon S, Flouriot A-C. BioRoot™ RCS a new biomaterial for root canal filling. https://www.septodontusa.com/sites/default/files/2019-04/CSC13_BioRoot%E2%84%A2%20RCS%20a%20new%20biomaterial%20for%20root%20canal%20filling_14.pdf. Accessed 31 May 2020.
34. Asgary S, Shahabi S, Jafarzadeh T, Amini S, Kheirieh S. The properties of a new endodontic material. J Endod. 2008;34:990–3.
35. Kogan P, He J, Glickman GN, Watanabe I. The effects of various additives on setting properties of MTA. J Endod. 2006;32:569–72.
36. Wiltbank KB, Schwartz SA, Schindler WG. Effect of selected accelerants on the physical properties of mineral trioxide aggregate and Portland cement. J Endod. 2007;33:1235–8.
37. Camilleri J, Montesin FE, Papaioannou S, McDonald F, Pitt Ford TR. Biocompatibility of two commercial forms of mineral trioxide aggregate. Int Endod J. 2004;37:699–704.
38. Tanomaru-Filho M, Jorge EG, Guerreiro Tanomaru JM, Gonçalves M. Radiopacity evaluation of new root canal filling materials by digitalization of images. J Endod. 2007;33:249–51.
39. Fonzar F, Mollo A, Venturi M, Pini P, Fonzar RF, Trullenque-Eriksso A, Esposito M. Single versus two visits with 1-week intracanal calcium hydroxide medication for endodontic treatment: one-year post-treatment results from a multicentre randomised controlled trial. Eur J Oral Implantol. 2017;1:29–41.
40. Mehta S, Verma P, Tikku AP, Chandra A, Bains R, Banerjee G. Comparative evaluation of antimicrobial

efficacy of triple antibiotic paste, calcium hydroxide, and a proton pump inhibitor against resistant root canal pathogens. Eur J Dent. 2017;11:53–7.
41. Kvist T, Molander A, Dahlén G, Reit C. Microbiological evaluation of one- and two-visit endodontic treatment of teeth with apical periodontitis: a randomized, clinical trial. J Endod. 2004;30:572–6.
42. Chávez De Paz LE, Dahlén G, Molander A, Möller Å, Bergenholtz G. Bacteria recovered from teeth with apical periodontitis after antimicrobial endodontic treatment. Int Endod J. 2003;36:500–8.
43. http://www.angelusdental.com/img/arquivos/2833_10502833_0111022019_bio_c_temp_bula_fechado.pdf. Accessed 31 May 2020.
44. Guerrero F, Mendoza A, Ribas D, Aspiazu K. Apexification: a systematic review. J Conserv Dent. 2018;21:462. https://doi.org/10.4103/JCD.JCD_96_18.
45. Gharechahi M, Ghoddusi J. A nonsurgical endodontic treatment in open-apex and immature teeth affected by dens invaginatus: using a collagen membrane as an apical barrier. J Am Dent Assoc. 2012;143:144–8.
46. Andreasen JO, Munksgaard EC, Bakland LK. Comparison of fracture resistance in root canals of immature sheep teeth after filling with calcium hydroxide or MTA. Dent Traumatol. 2006;22:154–6.
47. Nosrat A, Nekoofar MH, Bolhari B, Dummer PMH. Unintentional extrusion of mineral trioxide aggregate: a report of three cases. Int Endod J. 2012;45:1165–76.
48. Lin JC, Lu JX, Zeng Q, Zhao W, Li WQ, Ling JQ. Comparison of mineral trioxide aggregate and calcium hydroxide for apexification of immature permanent teeth: a systematic review and meta-analysis. J Formos Med Assoc. 2016;115:523–30.
49. Bücher K, Meier F, Diegritz C, Kaaden C, Hickel R, Kühnisch J. Long-term outcome of MTA apexification in teeth with open apices. Quintessence Int. 2016;47:473. https://doi.org/10.3290/j.qi.a35702.
50. Songtrakul K, Azarpajouh T, Malek M, Sigurdsson A, Kahler B, Lin LM. Modified apexification procedure for immature permanent teeth with a necrotic pulp/apical periodontitis: a case series. J Endod. 2020;46:116–23.
51. Cechella B, de Almeida J, Kuntze M, Felippe W. Analysis of sealing ability of endodontic cements apical plugs. J Clin Exp Dent. 2018;10:146–50.
52. Mente J, Hage N, Pfefferle T, Koch MJ, Dreyhaupt J, Staehle HJ, et al. Mineral trioxide aggregate apical plugs in teeth with open apical foramina: a retrospective analysis of treatment outcome. J Endod. 2009;35:1354–8.
53. Rajasekharan S, Martens LC, Cauwels RGEC, Anthonappa RP. Biodentine™ material characteristics and clinical applications: a 3-year literature review and update. Eur Arch Paediatr Dent. 2018;19:1. https://doi.org/10.1007/s40368-018-0328-x.
54. Martens L, Rajasekharan S, Cauwels R. Endodontic treatment of trauma-induced necrotic immature teeth using a tricalcium silicate-based bioactive cement. A report of 3 cases with 24-month follow-up. Eur J Paediatr Dent. 2016;17:24–8.
55. Sharma S, Sharma V, Passi D, Srivastava D, Grover S, Dutta SR. Large periapical or cystic lesions in association with roots having open apices managed nonsurgically using 1-step apexification based on platelet-rich fibrin matrix and biodentine apical barrier: a case series. J Endod. 2018;44:179–85.
56. Lee LW, Hsiao SH, Lin YH, Chen PY, Lee YL, Hung WC. Outcomes of necrotic immature open-apex central incisors treated by MTA apexification using poly(ε-caprolactone) fiber mesh as an apical barrier. J Formos Med Assoc. 2019;118:362–70.
57. Sisli SN, Ozbas H. Comparative micro–computed tomographic evaluation of the sealing quality of ProRoot MTA and MTA angelus apical plugs placed with various techniques. J Endod. 2017;43:147–51.
58. Drukteinis S, Peciuliene V, Shemesh H, Tusas P, Bendinskaite R. Porosity distribution in apically perforated curved root canals filled with two different calcium silicate-based materials and techniques: a micro-computed tomography study. Materials (Basel). 2019;12:1729. https://doi.org/10.3390/ma12111729.
59. Raveendran DK, Vanamala N, Murali Rao H, Keshava Prasad B, Mankar S, Graduate Student P, et al. Management of open apices with mineral trioxide aggregate and biodentine-a case report. IOSR J Dent Med Sci. 2019;18:9–13.
60. Ng YL, Mann V, Gulabivala K. Outcome of secondary root canal treatment: a systematic review of the literature. Int Endod J. 2008;41:1026. https://doi.org/10.1111/j.1365-2591.2008.01484.x.
61. Mente J, Leo M, Panagidis D, Saure D, Pfefferle T. Treatment outcome of mineral trioxide aggregate: repair of root perforations - long-term results. J Endod. 2014;40:790–6.
62. Gorni FG, Andreano A, Ambrogi F, Brambilla E, Gagliani M. Patient and clinical characteristics associated with primary healing of iatrogenic perforations after root canal treatment: results of a long-term Italian study. J Endod. 2016;42:211–5.
63. Yeung P, Liewehr FR, Moon PC. A quantitative comparison of the fill density of MTA produced by two placement techniques. J Endod. 2006;32:456–9.
64. Tsesis I, Fuss Z. Diagnosis and treatment of accidental root perforations. Endod Top. 2006;13:95. https://doi.org/10.1111/j.1601-1546.2006.00213.x.
65. Tsesis I, Rosenberg E, Faivishevsky V, Kfir A, Katz M, Rosen E. Prevalence and associated periodontal status of teeth with root perforation: a retrospective study of 2,002 patients' medical records. J Endod. 2010;36:797–800.
66. Hamama HH, Yiu CK, Burrow MF, Kahler B, Rossi-fedele G, Kim HH-E, et al. The influence of cervical preflaring on the amount of apically extruded debris

after root canal preparation using different instrumentation systems. J Endod. 2015;41:1–6.
67. Donnermeyer D, Viedenz A, Schäfer E, Bürklein S. Impact of new cross-sectional designs on the shaping ability of rotary NiTi instruments in S-shaped canals. Odontology. 2020;108:174–9.
68. Schäfer E, Dammaschke T. Development and sequelae of canal transportation. Endod Top. 2006;15:75–90.
69. Razcha C, Zacharopoulos A, Anestis D, Mikrogeorgis G, Zacharakis G, Lyroudia K. Micro-computed tomographic evaluation of canal transportation and centering ability of 4 heat-treated nickel-titanium systems. J Endod. 2020;46:675. https://doi.org/10.1016/j.joen.2020.01.020.
70. Mohammed Saed S, Ashley MP. Root perforations: aetiology, management strategies and outcomes. The hole truth. Br Dent J. 2016;220:171. https://doi.org/10.1038/sj.bdj.2016.132.
71. Lanker A, Fathey W, Samar S, Zakir M, Imranulla M, Pasha S. Non-surgical management of iatrogenic lateral root perforation: a case report. Int J Res Med Sci. 2018;6:1804.
72. Patel B. Iatrogenic perforations. In: Patel B, editor. Endod treatment, retreatment, and surgery. Mastering clinical practice. Cham: Springer International Publishing; 2016. p. 279–96.
73. Aidasani G, Mulay S. Management of iatrogenic errors: furcal perforation. J Int Clin Dent Res Organ. 2018;10:42–6.
74. Pace R, Giuliani V, Pagavino G. Mineral trioxide aggregate as repair material for furcal perforation: case series. J Endod. 2008;34:1130–3.
75. Mancino D, Meyer F, Haikel Y. Improved single visit management of old infected iatrogenic root perforations using Biodentine®. G Ital Endod. 2018;32:17–24.
76. Tek V, Türker SA. A micro-computed tomography evaluation of voids using calcium silicate-based materials in teeth with simulated internal root resorption. Restor Dent Endod. 2019;45:e5. https://doi.org/10.5395/rde.2020.45.e5.
77. Young GR. Contemporary management of lateral root perforation diagnosed with the aid of dental computed tomography. Aust Endod J. 2007;33:112–8.
78. Estrela C, Decurcio DA, Rossi-Fedele G, Silva JA, Guedes OA, Borges ÁH. Root perforations: a review of diagnosis, prognosis and materials. Braz Oral Res. 2018;32:e73. https://doi.org/10.1590/1807-3107bor-2018.vol32.0073.
79. Ha WN, Duckmanton P, Kahler B, Walsh LJ. A survey of various endodontic procedures related to mineral trioxide aggregate usage by members of the Australian Society of Endodontology. Aust Endod J. 2016;42:132–8.
80. Chin JS, Thomas MB, Locke M, Dummer PMH. A survey of dental practitioners in Wales to evaluate the management of deep carious lesions with vital pulp therapy in permanent teeth. Br Dent J. 2016;221:331–8.
81. Guivarc'h M, Jeanneau C, Giraud T, Pommel L, About I, Azim AA, et al. An international survey on the use of calcium silicate-based sealers in non-surgical endodontic treatment. Clin Oral Investig. 2020;24:417–24.
82. https://www.septodont.com.ru/sites/ru/files/2019-07/Septodont_BioRoot_Endo%20sealer%20or%20biological%20filler_JC.pdf. Accessed 31 May 2020.
83. Koch K, Brave DNA. A review of bioceramic technology in endodontics. Roots. 2013;1:6–13.
84. Prati C, Gandolfi MG. Calcium silicate bioactive cements: biological perspectives and clinical applications. Dent Mater. 2015;31:351. https://doi.org/10.1016/j.dental.2015.01.004.
85. Patel S, Ford TP. Is the resorption external or internal? Dent Update. 2007;34:218. https://doi.org/10.12968/denu.2007.34.4.218.
86. Patel S, Ricucci D, Durak C, Tay F. Internal root resorption: a review. J Endod. 2010;36:1107. https://doi.org/10.1016/j.joen.2010.03.014.
87. Roscoe MG, Meira JBC, Cattaneo PM. Association of orthodontic force system and root resorption: a systematic review. Am J Orthod Dentofac Orthop. 2015;147:610. https://doi.org/10.1016/j.ajodo.2014.12.026.
88. Velloso G, de Freitas M, Alves A, Silva A, Barboza E, Moraschini V. Multiple external cervical root resorptions after home whitening treatment: a case report. Aust Dent J. 2017;62:528–33.
89. Fuss Z, Tsesis I, Lin S. Root resorption - diagnosis, classification and treatment choices based on stimulation factors. Dent Traumatol. 2003;19:175–82.
90. Tronstad L. Root resorption - etiology, terminology and clinical manifestations. Dent Traumatol. 1988;4:241–52.
91. Aggarwal V, Singla M. Management of inflammatory root resorption using MTA obturation- a four year follow up. Br Dent J. 2010;208:287–9.
92. Pruthi PJ, Dharmani U, Roongta R, Talwar S. Management of external perforating root resorption by intentional replantation followed by Biodentine restoration. Dent Res J. 2015;12:488–93.
93. Alqedairi A. Non-invasive management of invasive cervical resorption associated with periodontal pocket: a case report. World J Clin Cases. 2019;7:863–71.
94. Mackeviciute M, Subaciene L, Baseviciene N, Siudikiene J. External root resorption - try to save or extract: a case report. J Cont Med A Dent. 2018;3:32–5.
95. Estrela C, Guedes OA, Rabelo LEG, Decurcio DA, Alencar AHG, Estrela CRA, et al. Detection of apical inflammatory root Resorption associated with Periapical lesion using different methods. Braz Dent J. 2014;25:404–8.
96. Laux M, Abbott PV, Pajarola G, Nair PNR. Apical inflammatory root resorption: a correlative radiographic and histological assessment. Int Endod J. 2000;33:483–93.

97. Topçuoğlu HS, Düzgün S, Ceyhanlı KT, Aktı A, Pala K, Kesim B. Efficacy of different irrigation techniques in the removal of calcium hydroxide from a simulated internal root resorption cavity. Int Endod J. 2015;48:309–16.
98. Torres CP, Apicella MJ, Yancich PP, Parker MH. Intracanal placement of calcium hydroxide: a comparison of techniques, revisited. J Endod. 2004;30:225–7.
99. van der Sluis LWM, Wu MK, Wesselink PR. The evaluation of removal of calcium hydroxide paste from an artificial standardized groove in the apical root canal using different irrigation methodologies. Int Endod J. 2007;40:52–7.
100. Nandini S, Velmurugan N, Kandaswamy D. Removal efficiency of calcium hydroxide intracanal medicament with two calcium chelators: volumetric analysis using spiral CT, an in vitro study. J Endod. 2006;32:1097–101.
101. Salzano S, Tirone F. Conservative nonsurgical treatment of class 4 invasive cervical resorption: a case series. J Endod. 2015;41:1907–12.
102. Eftekhar L, Ashraf H, Jabbari S. Management of invasive cervical root resorption in a mandibular canine using biodentine as a restorative material: a case report. Iran Endod J. 2017;12:386–9.
103. Chércoles-Ruiz A, Sánchez-Torres A, Gay-Escoda C. Endodontics, endodontic retreatment, and apical surgery versus tooth extraction and implant placement: a systematic review. J Endod. 2017;43:679. https://doi.org/10.1016/j.joen.2017.01.004.
104. Esposito M, Trullenque-Eriksson A, Tallarico M. Endodontic retreatment versus dental implants of teeth with an uncertain endodontic prognosis: 3-year results from a randomised controlled trial. Eur J Oral Implantol. 2018;11:423–38.
105. Tang Y, Li X, Yin S. Outcomes of MTA as root-end filling in endodontic surgery: a systematic review. Quintessence Int. 2010;41:557–66.
106. Solanki N, Venkappa K, Shah N. Biocompatibility and sealing ability of mineral trioxide aggregate and biodentine as root-end filling material: a systematic review. J Conserv Dent. 2018;21:10. https://doi.org/10.4103/JCD.JCD_45_17.
107. Chen I, Karabucak B, Wang C, Wang HG, Koyama E, Kohli MR, et al. Healing after root-end microsurgery by using mineral trioxide aggregate and a new calcium silicate-based bioceramic material as root-end filling materials in dogs. J Endod. 2015;41:389–99.
108. Tang JJ, Shen ZS, Qin W, Lin Z. A comparison of the sealing abilities between Biodentine and MTA as root-end filling materials and their effects on bone healing in dogs after periradicular surgery. J Appl Oral Sci. 2019;27:e20180693. https://doi.org/10.1590/1678-7757-2018-0693.
109. Vivan RR, Guerreiro-Tanomaru JM, Bernardes RA, Reis JMSN, Hungaro Duarte MA, Tanomaru-Filho M. Effect of ultrasonic tip and root-end filling material on bond strength. Clin Oral Investig. 2016;20:2007–11.
110. Tawil PZ. Periapical microsurgery: can ultrasonic root-end preparations clinically create or propagate dentinal defects? J Endod. 2016;42:1472–5.
111. Floratos S, Kim S. Modern endodontic microsurgery concepts: a clinical update. Dent Clin N Am. 2017;61:81. https://doi.org/10.1016/j.cden.2016.08.007.