Review Article

Root Perforation Repair with Calcium Silicate Cements: Part 1- Basic Knowledge and Treatment Outcomes

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Abstract

Root perforation can occur due to pathological conditions, iatrogenic factors during root canal treatment, or post-space preparation in the restorative procedure. The perforation creates a pathway of infection connecting the root canal system and the external root surface making endodontic treatment more complicated. Diagnosis of root perforation can be achieved through comprehensive clinical and radiographic evaluations. The classification of root perforations has been based on 1) the location of the root perforation, 2) the size of the root perforation, and 3) the time to repair the root perforation. The principles of managing root perforation involve eliminating any infection at the perforation site and sealing the perforation with a material that is biocompatible and provides a good seal. Currently, calcium silicate cements are used as root repair materials, with mineral trioxide aggregate (MTA) being the first widely adopted material due to its excellent sealing ability, antibacterial properties, and biocompatibility. However, MTA has drawbacks such as long setting time, difficult handling, and potential tooth discoloration. Therefore, new types of calcium silicate cement materials have been developed, maintaining the primary components of dicalcium silicate and tricalcium silicate, and used for root perforation repair. Evaluating the success of root perforation repairs is generally based on a combination of clinical and radiographic examinations. In the average follow-up period ranging from 6 to 168 months, the success rates of root perforation repair with calcium silicate cement materials (mostly repaired with original MTA) ranged from 73.3–100% according to the strict criteria (healed). The success rates were 100% according to the lenient criteria (healed or healing). Most studies observed a reduction in the size of periapical lesions within 6 months after treatment, and complete healing of the lesions within 12-24 months. However, late failures after treating root perforations can be observed in the 2-3 years range postoperatively or longer. Long-term follow-up of the treatment is necessary to ensure the stability of the repair without peri-radicular lesions or root fractures. The main prognostic factors to outcomes of root perforation repair will be further described in the next article (part 2).

Keywords: calcium silicate cement, prognostic factors, root perforation repair, treatment outcome

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1. Introduction

The main objective of root canal treatment is to eliminate infection within the root canal system to treat and prevent inflammation of the periapical periodontal tissue (apical periodontitis) [1]. Root perforation creates a pathway connecting the root canal system and the external root surface [2]. Root perforation can occur due to various pathological conditions (e.g. root caries, root resorption), or iatrogenic factors during root canal treatment procedures (e.g. access opening, locating canal orifices, or root canal preparation). Additionally, root perforation can occur during post-space preparation after root canal treatment [3, 4].

Root perforation can impact the success of root canal treatment, especially if the perforation is large and located near the alveolar crest and epithelial attachment. Large perforations may make it difficult to achieve a tight seal during repair [3]. Furthermore, perforations near the alveolar crest may allow bacteria from the oral cavity to re-enter the root canal, potentially causing infection and inflammation of the periodontal tissue, leading to further tissue destruction and possible tooth loss if not promptly managed [5-7]. Accurate and timely diagnosis and appropriate management of root perforation can prevent these adverse outcomes [4, 8]. The objective of this article (part 1) is to describe basic knowledge and treatment outcomes of root perforation repair with calcium silicate cement. The main prognostic factors to the treatment outcomes will be further described in the next article (part 2).

2. Basic knowledge

2.1 Diagnosis of Root Perforation

Diagnosis of root perforation can be achieved through clinical and radiographic evaluations [4, 9]. Clinically, it involves examining the patient's symptoms and signs such as sudden pain during treatment, bleeding from the root canal or pulp chamber during preparation (not from residual pulp tissue), and severe deviation of the root canal and file direction.

Confirmation of root perforation can be done using an apex locator attached to an endodontic explorer or file to detect the suspected perforation site [10]. A dental operating microscope can help identify the perforation's location and size if visible from the root canal entrance [11].

Radiographically, periapical films or vertical bitewing radiographs can show signs of root perforations such as bone resorption adjacent to the perforation site, overextended root canal filling materials, radiolucent lines extending from the root canal wall to the periodontal space, or files extending outside the root canal. However, two-dimensional radiographic evaluation may have limitations, especially with labial, buccal, lingual, or palatal perforations due to the overlap with the remaining root structure. A parallel technique with horizontal tube shifts may be necessary for accurate diagnosis [12].

Cone-beam computed tomography (CBCT) offers a more precise three-dimensional evaluation of the perforation's location and size compared to periapical films, particularly for stripping-type perforations [9, 13]. From the study by Shemesh et al. (2011) comparing the accuracy of detecting stripping-type root perforations between CBCT and periapical film, CBCT was significantly more accurate in detecting the root perforations [14]. However, CBCT may be limited in teeth with root canal fillings or metal posts due to scattering artifacts.

Therefore, clinical and radiographic evaluations are essential for accurate diagnosis, prognosis, and treatment planning for root perforations [2, 15].

2.2 Classification of Root Perforation

The classification of root perforations has been based on factors that may affect the prognosis of teeth with root perforations. These factors include 1) the location of the root perforation, 2) the size of the root perforation, and 3) the time to repair the root perforation. According to the three factors, Fuss and Trope (1996) [3] classified the prognosis into two categories: good prognosis and poor prognosis.

The classification of root perforations by location includes lateral perforation and furcation perforation (**Figure 1**). Lateral perforations are further divided into coronal perforation, crestal perforation, and apical perforation. Furcation perforations are also subdivided into direct type, found on the pulpal floor of multi-rooted teeth, and strip perforation, found in the danger zone of multi-rooted teeth. Additionally, root perforations occurring in specific areas of the root can be classified into coronal one-third, middle one-third, and apical one-third.

Based on the size of the root perforation, they can be classified into small and large perforations. It has been suggested that a small root perforation should not exceed the tip of a size 15 or 20 root canal file. Larger perforations or those resulting from the preparation of the post space are classified as large root perforations.

For classification based on the time from the occurrence of the perforation to its repair, perforations can be divided into fresh perforation with immediate repair and old perforation, which has been present for a long time and leads to bacterial infection within the oral cavity, causing damage to the surrounding periodontal tissues.

If the perforation is at the crestal level and has been present for a long time or is large, the prognosis is poor. This is because perforations at the crestal level have a higher chance of reinfection from oral bacteria entering through the perforation, leading to the destruction of the surrounding periodontal tissues. Repairing such perforations to achieve a tight seal is difficult, resulting in a poorer prognosis compared to smaller perforations below the crestal level that are repaired promptly (**Table 1**).

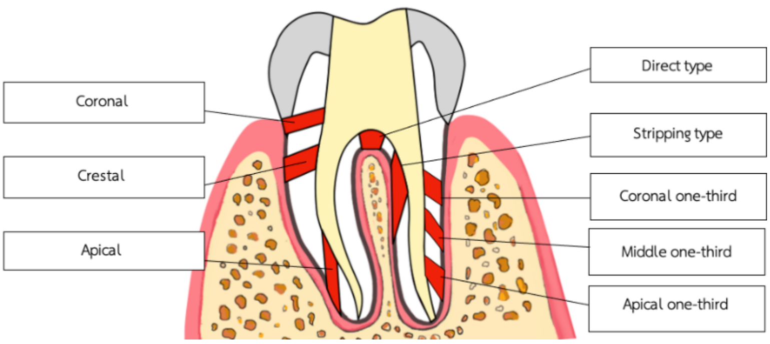

Figure 1 Root perforations are classified based on the locations of perforation.

Table 1 Classification of root perforations and their prognoses (adapted from Fuss and Trope, 1996 [3])

Factors of perforations	Good prognosis	Poor prognosis
Location	Coronal or radicular perforations below the alveolar crest	The alveolar crest
Size	Small, not exceed the tip of a size 15 or 20 root canal file	Large or during post-space preparation
Time to repair	Immediate repair, or delayed repair but under root-canal infection control	Delayed repair without treatment or root-canal infection control

In 2014, the American Association of Endodontists (AAE) classified the types of root perforations based on factors affecting prognosis into favorable prognosis, questionable prognosis, and unfavorable prognosis [16]. The classification considers:

1. Location of the perforation along with the presence of sulcular communication, divided into apical perforation, mid-root perforation, furcation perforation, and crestal perforation.

2. Timing of perforation repair, categorized into immediate repair, delayed repair, and no repair.

3. Size of the perforation, is classified as small, medium, and large, although the specific definitions of these sizes are not established.

According to AAE, the prognosis for teeth with root perforations is shown in **Table 2**.

2.3 Management of Root Perforation

The management of root perforation has become crucial because if there remains a connection between the inside and outside of the root canal through the perforation, it will be impossible to control the infection in that particular root canal. The principles of managing root perforation involve eliminating any infection at the perforation site (if present) and sealing the perforation with a material that is biocompatible and provides a good seal [3, 4, 15].

Table 2 Prognosis of teeth with root perforations according to various factors, based on the American Association of Endodontists [16].

Factors of perforations	Favorable prognosis	Questionable prognosis	Unfavorable prognosis
Location	Apical area of root with no sulcular communication or bony defect	The middle area of root or furcation with no sulcular communication or bony defect	Apical, crestal, or furcation area with sulcular communication or periodontal/ bony defect
Time to repair	Immediate repair	Delayed repair	No repair or gross extrusion of repairing materials
Size	Small	Moderate	Large

There are two main methods for managing root perforation: 1) non-surgical repair and 2) surgical repair [15]. Generally, non-surgical repair is the first choice, especially when the perforation is in a visible location that can be accessed and sealed from inside the tooth under a dental microscope. In cases where there is bone destruction at the perforation site, a matrix (e.g. collagen sponge) may be used along with the repair material to ensure the material remains confined to the perforation site without extending into the surrounding periodontal tissues, thus ensuring a good seal between the repair material and the perforation walls [17]. If the matrix technique is not used, extrusion of repair material may occur particularly in teeth with large perforations (**Figure 2**), which potentially leads to the persistence of peri-radicular lesions.

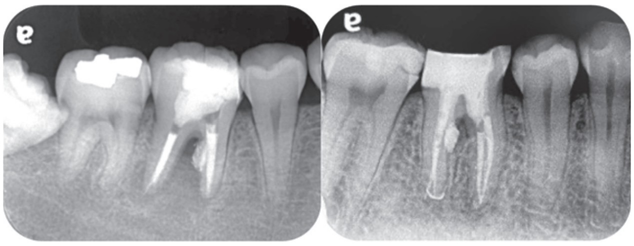

Figure 2 (left and right): Extrusion of root-repair material into the areas of peri-radicular lesions at the large perforation sites when the internal matrix is not used.

Surgical repair may be chosen when the perforation is large and in a location that cannot be repaired through coronal access. This method can also be used in conjunction with non-surgical repair if a good seal cannot be achieved by repairing through coronal access alone. This might involve a flap operation to gain better access [18], such as in the case of repairing a perforation caused by external root resorption. Other options for managing perforated root canals include root resection in multi-rooted teeth, considering factors like the divergence of the roots, the location and extent of the perforation, the amount of supporting bone for the remaining roots, and the patient's oral health [3, 6, 8].

2.4 Root-repair Material

Root-repair materials have become crucial due to their ability to create a tight seal and biocompatibility with tissues, enhancing the success of root perforation treatments. Historically, various materials have been used to repair perforations, such as amalgam, zinc oxide-eugenol cement, calcium hydroxide, glass ionomer cement, IRM, resin composites, and Super EBA [19, 20]. However, these materials have limitations such as poor sealing, moisture sensitivity, lack of strength, or low biocompatibility.

Currently, calcium silicate cements are used as root repair materials, with mineral trioxide aggregate (MTA) being the first widely adopted material due to its excellent sealing ability, antibacterial properties, and biocompatibility [21]. A laboratory study has shown that MTA has the least leakage compared to amalgam and IRM in root perforation repair [22]. Daoudi and colleagues also found that MTA exhibited less leakage than glass ionomer cement when used for root perforation repair [23]. In an animal study, Pitt Ford and colleagues observed that MTA did not cause periodontal tissue inflammation when used to repair root perforations in furcation areas, unlike amalgam [24]. Laboratory comparisons of antibacterial properties among amalgam, zinc oxide-eugenol, Super EBA, and MTA revealed that MTA had superior antibacterial effects in both oxygen-rich and oxygen-poor conditions (facultative anaerobes) [25].

Despite MTA's advantages in root repair, it has drawbacks such as long setting time, difficult handling, and potential tooth discoloration. Therefore, new calcium silicate cement materials have been developed, maintaining the primary components of dicalcium silicate and tricalcium silicate but modifying other compounds. For example, bismuth oxide has been replaced with zirconium oxide to reduce tooth discoloration. Calcium sulfate ($CaSO_4$) has been removed, or calcium chloride ($CaCl_2$) has been added to shorten the setting time [26]. Examples of new calcium silicate cements are MTA Angelus® (Angelus, Londrina, PR, Brazil), MTA Repair HP® (Angelus), Biodentine® (Septodont, Saint-Maur-des-Fosses, France), iRoot® BP Plus (Innovative Bioceramix Inc., Vancouver, Canada), EndoSequence® BC RRM™ (Brasseler, GA, USA), BIO-C® Repair (Angelus), RetroMTA® (BioMTA, Seoul, Korea), C-Root BP (C-Root Dental Medical Devices, Beijing, China), and Bio-MA (M-Dent/SCG, Bangkok, Thailand) [27].

2.5 Types of Calcium Silicate Cement Materials for Root Perforation Repair

The types of calcium silicate cement materials for root repairing and other purposes can be categorized based on their basic composition and usage into five types [27] as follows:

- Type 1: Mixed MTA without additive (e.g. ProRoot MTA).

- Type 2: Mixed MTA with additive (e.g. Bio-MA, MTA Angelus, and MTA Repair HP).

- Type 3: Ready-mixed MTA with additive (e.g. BIO-C® Repair).

- Type 4: Mixed tricalcium/dicalcium silicate cement with additive (e.g. Biodentine).

- Type 5: Ready-mixed tricalcium/dicalcium (or strontium) silicate cement with additive (e.g. C-Root BP, TotalFill).

The additive is commonly an accelerator to fasten setting time or other ingredient(s) (e.g. calcium phosphate) to promote biomineralization [27].

Although the success rate of root perforation repair using calcium silicate cement materials is expected to be high, the number of patients, follow-up periods, definitions of success, and factors affecting success vary across studies. According to a systematic review by Siew et al. (2015) [28], the overall success rate of non-surgical root perforation repair using various repair materials was 72.5%. When considering only the use of MTA calcium silicate cement, the success rate was higher at 80.9%. However, there were no reports of the success rates of root perforation repair using other calcium silicate cement materials at that time.

Currently, more studies have been conducted on the outcomes of root perforation repair, and new calcium silicate cement materials have been developed in addition to MTA. Therefore, it is necessary to update and compare the success rates of all root perforation repairs, as well as the factors affecting the success of such repairs.

3. Treatment Outcomes of Root Perforation Repair with Calcium Silicate Cements

3.1 Evaluation of Success in Root Perforation Repair

Since 1999, clinical studies have reported on the success of repairing root perforations using calcium silicate cement materials, with MTA being the first and most extensively studied material [28]. The methods for evaluating the success of root perforation repairs generally include clinical examination and radiographic examination, with each study potentially having different definitions of success [29-38].

In clinical examinations, the assessment is based on the patient's symptoms and clinical signs, such as visual inspection, percussion, palpation, mobility testing, and periodontal examination for the presence of periodontal pockets, especially in the area of perforation repair. Radiographic assessments evaluate the appearance of the lesion and the periodontal tissues around the root, including the area of the perforation repair.

For the radiographic assessment of periapical lesions, Ørstavik and colleagues proposed the Periapical Index (PAI) in 1986 [39]. The PAI scores the area around the root apex on radiographs of teeth that have undergone root canal treatment, with scores ranging from 1 to 5. For teeth with multiple roots, the score of the root with the highest score represents the tooth. The PAI score descriptions are as follows: *PAI score 1*: normal periapical tissues, *PAI score 2*: small changes in bone structure around the root apex but not pathologic, *PAI score 3*: structural changes and initial bone loss around the root apex, indicating pathology, *PAI score 4*: radiolucent lesion with clear boundaries indicating bone destruction around the root apex, and *PAI score 5*: extensive radiolucent lesion with diffuse boundaries indicating widespread bone destruction around the root apex. Teeth with an evaluation score of 1 or 2 indicate a normal periapical condition, while teeth with a score of 3-5 indicate an increasing severity of periapical pathology according to the score.

Later, Pontius et al. (2013) [36] presented the Root Perforation Index (RPI) score to evaluate the treatment outcome of root perforation repair. This index is adapted from the PAI score to assess radiographs specifically at the perforation site, with the following criteria: *RPI score 1*: normal tissue around the perforation site, *RPI score 2*: slight changes in bone structure at the perforation site, but not pathological, *RPI score 3*: changes in bone structure at the perforation site with initial bone loss indicating pathology, *RPI score 4*: radiolucent lesion with clear boundaries due to bone destruction at the perforation site, and *RPI score 5*: radiolucent lesion with bone destruction spreading from the perforation site, with unclear boundaries.

For treatment outcome evaluation of root perforation repairs, most studies and this review use Friedman and Mor (2004) [40] criteria according to a combination of clinical and radiographic examinations, which correspond to the peri-radicular (either the periapical area or perforation site) healing process as follows: *Healed*: no clinical symptoms, and normal peri-radicular area on radiograph (PAI or RPI score 1-2), *Healing*: no clinical symptoms, with a reduction in the size of the peri-radicular lesion on radiograph (decrease in PAI or RPI score), *Disease*: with one of these conditions (1) no clinical symptoms but a newly developed or unchanged periapical lesion, or an increase in size (increase in PAI or RPI score), or (2) clinical symptoms with or without any peri-radicular radiolucency.

In the study of treatment outcomes for teeth with root perforations, the outcome can be grouped and dichotomized as '*success*' or '*failure*' depending on two evaluation criteria [40] (**Figure 3**): (a) the **strict** criteria: '*success*'- no clinical symptoms and no periapical lesions, indicating the teeth with healed periapical lesions only; and (b) the **lenient** criteria: '*success*'- no clinical symptoms, either with no periapical lesions or with periapical lesions that have reduced in size, indicating teeth with both healed and healing periapical lesions on radiographs. Using the former criterion results in a lower success rate compared to using the latter criterion.

Additionally, the treatment outcome of root perforation repair can be assessed as *functional retention*- no clinical symptoms, with or without any peri-radicular radiolucency. A peri-radicular lesion (if any) could be pre-existing or newly developed after treatment.

3.2 Success Rates of Root Perforation Repair with Calcium Silicate Cements

As of the end of 2023, a search in various databases identified 12 studies on the success rate of root perforation repairs (**Tables 3 and 4**). The terms- root perforation repair and clinical study or outcome, are used for literature searching in the PubMed database. After excluding case reports, the included studies are 2 case-series studies, 5 retrospective cohort studies, 2 prospective cohort studies, 2 randomized controlled trials (RCTs), and 1 systematic review with meta-analysis. In these studies, the average follow-up period ranged from 6 to 168 months. The success rates ranged from 73.3–100% according to the strict criteria (healed), and was 100% according to the lenient criteria (healed or healing) (**Tables 3-4**). In addition, potential influencing factors to the outcome of root perforation repair are briefly reported in contexts, which the main factors will be further described in the next article (part 2).

The studies can be grouped into three categories based on the type of calcium silicate cement used for repairing perforations: (a) Portland cement with no accelerators (ProRoot MTA), (b) Portland cement with accelerators (Bio-MA), and (c) Tricalcium dicalcium silicate cement with accelerators (Biodentine). Only the outcomes of root perforation repairs with calcium silicate cement types 1, 2 and 4 [27] have been reported (**Tables 3-4**). There are no clinical studies yet for other newly developed materials (type 3 and 5) for root perforation repair.

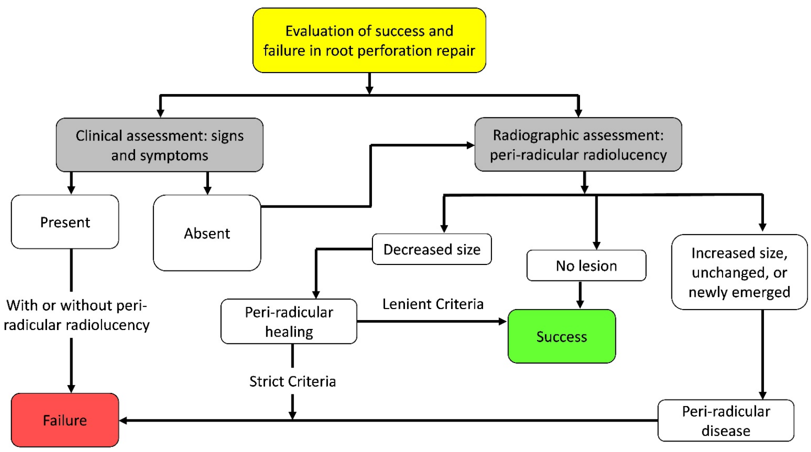

Figure 3 Flow chart in evaluation of success and failure in root perforation repair.

Table 3 Success rates for teeth with repaired root perforations using calcium silicate cement, evaluated at the *peri-radicular area*

Repair material	Study type	Author (year)	Teeth (n)	Recall period (months)	Recall rate (%)	Evaluation criteria	Healed rate (%)	Healing rate (%)	Disease (%)
Mixed MTA without additive or accelerator (Type 1, ProRoot MTA)	Case series	Main et al. (2004)	16	12-45	100	Healed or diseased	100	N/A	-
		Pace et al. (2008)	10	12-60	100	Healed or diseased	90	N/A	10
	Retrospective cohort studies	Mente et al. (2010)	21	13-65 (median=33)	81	Healed or diseased	86	N/A	14
		Krupp et al. (2013)	90	12-120 (median= 34.8)	70	Healed or diseased	73.3	N/A	26.7
		Pontius et al. (2013)	50	6-116 (median=37)	71	Periapical index score	94	N/A	6
		Mente et al. (2014)	64	12-107 (median=33)	81	Healed or diseased	86	N/A	14
	Prospective cohort studies	Gorni et al. (2016)	110	12-96 (median=48)	100	Healed or diseased	92	N/A	9
		Gorni et al. (2022)	124	12-168 (median=144)	100	Healed or diseased	93	N/A	8
	Randomized controlled trials	Tungsuksomboon et al. (2021)	9	9-16	100	Healed, healing, or diseased	100	N/A	-
		Tungputsa et al. (2024)	23	12-56 (median=23.5)	100	Healed, healing, or diseased	82.6	13	4.4
	Systematic review and meta-analysis	Siew et al. (2015)	12 Studies	at least 12	71-100	Healed or diseased	80.9	N/A	N/A

Table 3 Success rates for teeth with repaired root perforations using calcium silicate cement, evaluated at the *peri-radicular area* (Continued)

Repair material	Study type	Author (year)	Teeth (n)	Recall period (months)	Recall rate (%)	Evaluation criteria	Healed rate (%)	Healing rate (%)	Disease (%)
Mixed MTA with additive or accelerator (Type 2, Bio-MA)	Randomized controlled trials	Tungsuksomboon et al. (2021)	13	9-16	100	Healed, healing, or diseased	92.3	7.7	N/A
		Tungputsa et al. (2024)	21	12-56 (median=23.5)	100	Healed, healing, or diseased	85.7	14.3	N/A
Mixed tricalcium/ dicalcium silicate cement with additive or accelerator (Type 4, Biodentine)	Retrospective observational studies	Mancino et al. (2018)	51	18-64	100	Healed or diseased	94	N/A	6

Table 4 Success rates for teeth with repaired root perforations using calcium silicate cement, evaluated at the *perforation site*

Repair material	Study type	Author (year)	Teeth (n)	Recall period (months)	Recall rate (%)	Evaluation criteria	Healed rate (%)	Healing rate (%)	Disease (%)
Mixed MTA without additive or accelerator (Type 1, ProRoot MTA)	Retrospective cohort studies	Pontius et al. (2013)	50	6-116 (median=37)	71	Root perforation index score	96	N/A	4
	Randomized controlled trials	Tungputsa et al. (2024)	23	21	12-56 (median=23.5)	Healed, healing, or diseased	95.7	4.3	N/A
Mixed MTA with additive or accelerator (Type 2, Bio-MA)	Randomized controlled trials	Tungputsa et al. (2024)	21	12-56 (median=23.5)	100	Healed, healing, or diseased	90.5	9.5	N/A

For the healing rate of lesions after root perforation repair with calcium silicate cement materials, most studies observed a reduction in the size of periapical lesions within 6 months after treatment, and complete healing of the lesions within 12-24 months [29-38].

3.2.1 Success Rates of Root Perforation Repair Using Mixed MTA without Additive or Accelerator (Type 1)

Clinical studies on non-accelerated, mixed MTA materials for repairing root perforations have only been conducted on the original MTA (ProRoot MTA) (**Tables 3 and 4**). According to a case series reported by Main et al. (2004) [32] involving the use of the MTA to repair root perforations in 16 teeth with a follow-up period of 12-45 months, the success rate based on the strict healing criteria (healed) was 100%. All cases showed complete healing of periapical lesions without the occurrence of new lesions related to the perforation in radiographic images. Later, Pace et al. (2008) [35] used the MTA to repair perforations at the furcation area in 10 teeth with a follow-up period of 12-60 months, finding a success rate of 90% based on the strict healing criteria. Healing of the peri-radicular lesions was observed at the both perforation and periapical areas, with no material extrusion beyond the perforation site. In this study, most perforations were recent and less than 2 mm in size.

A retrospective cohort study by Mente et al. (2010) [33] involved a sample of 21 teeth, most with perforations at the alveolar bone level (50%), untreated immediately (70%), and less than 3 mm in size (80%). The success rate based on the strict healing criteria was 86%, with a failure rate of 14%, mainly due to longitudinal root fractures rather than related to the repair material. In addition, no significant factors influencing success were found. In a follow-up study by the same group (Mente et al. 2014) [34], involving 64 teeth with a longer mean follow-up period of 107 months, the success rate was 86%, the failure rate was 14%, and the functional rate was 92%. Both studies demonstrated the same high success rates, which was attributed to good control of inflammation and infection at the perforation site and within the root canal before repair to sealing of the perforation by experienced endodontists. In these studies, two factors influencing success were identified: the treatment provider and the use of a post or screw after treatment [33, 34], which will be further described in part 2.

A retrospective cohort study by Krupp et al. (2013) [31] involving 90 teeth with root perforation repairs by the MTA and a follow-up period of 12-120 months found a strict healing success rate of 73.3%. This lower success rate compared to previous studies using the MTA may be due to the complexity and delayed repair of root perforations in teeth referred from general dentists, leading to bone-destruction lesions at the perforation site and communication with the oral cavity.

The retrospective study by Pontius et al. (2013) [36], on the outcomes of root perforation repair using the MTA in 50 teeth with a follow-up period of 6-116 months, reported an overall success rate of 90% according to the strict healing criteria. In addition, it was found that there was a 94% success rate according to the periapical index score of the peri-radicular lesions. This study also specifically evaluated the success rate at the root perforation site using the root perforation index score, which showed a 96% success rate. Evaluating success specifically at the root perforation site, instead of the peri-radicular area, is likely a more direct assessment of the effectiveness of MTA as a repair material. Additionally, this study identified factors influencing the success of the treatment, including the location of the root perforation, and the quality of the coronal restoration before perforation repair. The success rate decreased when the perforation was at the level of the alveolar bone crest, due to its proximity to the epithelial attachment, increasing the risk of contamination from the oral environment. Furthermore, if the quality of the coronal restoration before treatment was poor and not corrected (e.g., with leaky margins or recurrent decay), it would allow microbial leakage into the perforation and root canal before, during, and after treatment, thereby reducing the success rate. Additionally, the treatment in females showed a higher success rate compared to that in males (97% vs. 77%, respectively), though the explanation of this finding remains unclear.

A systematic review and meta-analysis by Siew et al. (2015) [28] included studies on root perforation repair using MTA in non-surgically treated permanent teeth with at least one year of follow-up. The study found an 80.9% overall success rate according to the strict healing criteria. Factors associated with successful treatment included the absence of lesions related to the perforation site and the tooth being in the maxilla. The presence of lesions indicates periodontal destruction around the area, increasing the chance of the repair material extruding outside the root, which may affect long-term adaptation. Additionally, maxillary teeth showed a higher success rate compared to mandibular teeth, though this finding remains unexplained.

From a prospective study by Gorni et al. (2016) [29], the MTA was used as the material for repairing root perforations in 110 teeth with the objectives of studying the healed rate of lesions according to the strict criteria and the likelihood of new peri-radicular lesions occurring after root perforation repair, with a follow-up period of 12-96 months. It was found that there was a 92% healed (success) rate (101 teeth) and a relatively low incidence of new lesions development in the first 5 years. However, an increase in new lesion development was found after 8 years post-treatment. Factors affecting lesion healing included gender, periodontal pocket depth, and the size and location of the root perforation, which will be further discussed in part 2.

Gorni et al. (2022) [30] continued the study to observe long-term success rates and identify factors affecting success rates, with the longest follow-up period being 168 months. The study found that at the 2-year follow-up, the success rate according to the strict healing criteria was 93% (115 teeth), consistent with their 1st phase study showing good initial healing. However, in recall periods up to 14 years, the success rate declined, with a tendency for success rates to decrease over longer periods. In the majority of failed cases, it was found that the MTA repair material at the root perforation site had disappeared, possibly due to the method of repair, which placed the repair material only at the perforation site without filling the entire root canal of the perforated root. This resulted in insufficient material bulk to reinforce the root and decrease the chance of long-term root fractures. Other factors influencing treatment success included having a periodontal pocket depth greater than 4 mm and a root perforation size greater than 3 mm. A periodontal pocket depth greater than 4 mm decreases the success rate due to the increased risk of contamination from the oral cavity, while a perforation size greater than 3 mm reduces the amount of remaining root dentin, affecting tooth strength and increasing the risk of root fracture over time.

A pilot clinical randomized controlled trial by Tungsuksomboon et al. (2021) [37], using the original MTA without accelerator to repair root perforations in 9 teeth with a follow-up period of 9-16 months, found a 100% success rate according to the lenient healing criteria (healed and healing in progress). This study compared the original MTA with the MTA with accelerator and found no significant difference in the success rates between the two materials. Later, a clinical randomized controlled trial by Tungputsa et al. (2024) [38] used MTA to repair root perforations in 23 teeth with a follow-up period of 12-56 months, evaluating treatment outcomes at two radiographic positions: the root perforation site and the peri-radicular area, along with clinical assessments. At the root perforation site, the success rate according to the lenient healing criteria was 100% (23 teeth), with healed and healing rates of 95.7% and 4.3%, respectively. Considering the success rate at the peri-radicular area, the lenient healing criteria showed a 95.6% success rate (22 teeth), with healed and healing rates of 82.6% and 13.3%, respectively, as shown in **Tables 3 and 4**. No significant factors affecting the success of root perforation repair treatment were found.

3.2.2 Success Rate of Root Perforation Treatment Using Mixed MTA with Additive or Accelerator (Type 2)

In the clinical randomized controlled trial by Tungsuksomboon et al. (2021) [37], an MTA material with accelerator (Bio-MA) was used to repair root perforations in 13 teeth with a follow-up period of 9-16 months. It was found that the success rate according to the lenient healing criteria was 100%, with the healed rate was 92.3%, and the healing rate was 7.7%.

Later, from the clinical randomized controlled trial by Tungputsa et al. (2024) [38], Bio-MA was used to repair root perforations in 21 teeth with a follow-up period of 12-56 months and evaluation of the success at both the root perforation site and the peri-radicular area. It was found that the success rate according to the lenient healing criteria at the root perforation site was 100% (21 teeth), with a healed rate of 90.5% and a healing rate of 9.5%. At the peri-radicular area, the success rate according to the lenient healing criteria was also 100% (21 teeth), with a healed rate of 85.7% and a healing rate of 14.3%, as shown in **Table 4**. No factors affecting the success of root perforation repair treatment were found, possibly due to the high success rate and the fact that most cases had no preoperative lesions at the perforation site or communication with the oral cavity, along with good infection control within the root canal and at the perforation area before the repair. Additionally, no differences in the success rates were found between the MTA materials with and without an accelerator (**Tables 3-4**).

3.2.3 Success Rate of Root Perforation Treatment Using Mixed Tricalcium/Dicalcium Silicate Cement with Additive or Accelerator (Type 4)

The retrospective observational study by Mancino et al. (2018) [41]studied the effects of using the fast-set calcium silicate material (i.e. Biodentine) to repair root perforations that had been present for more than 6 months to 1 year in 51 teeth with a follow-up period of 18-64 months, it was found that the success rate according to the strict healing criteria was 94% (48 teeth). This shows a relatively high success rate, even for the perforations that had not been treated for a long time and had peri-radicular lesions before treatment from alveolar bone destruction. This may be due to good control of inflammation and infection within the root canal and at the perforation area before repair, as well as using the repair material with good sealing properties, fast setting time, and ability to set in the presence of slight moisture (**Table 3**).

Conclusion

Currently, clinical studies on the success of repairing root perforations with calcium silicate cement materials are mostly studied on the original ProRoot MTA material. With a follow-up period of at least 12 months, success rates of root perforation repair with calcium silicate cements are high at 73.3-100% depending on the assessment criteria. However, late failures after treating root perforations can be observed in the 2-3 years range postoperatively or longer. Therefore, long-term follow-up of the treatment is necessary to ensure the stability of the repair without peri-radicular lesions or root fractures. The main prognostic factors to outcomes of root perforation repair will be described in the next article (part 2).

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