Endodontic Treatment Approaches of Immature Permanent Teeth with Necrotic Pulp

Kök Gelişimi Tamamlanmamış Nekrotik Pulpalı Daimi Dişlerde Endodontik Tedavi Yaklaşımları

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ABSTRACT

Pulp necrosis in immature permanent teeth results in the cessation of root development. In such teeth, pulp necrosis is commonly attributed to factors such as caries or trauma. Endodontic treatment of immature teeth with open apices presents various clinical challenges, particularly concerning root canal preparation and obturation, which require meticulous attention. Treatment options for immature teeth include conventional root canal therapy, apexification, creation of an apical barrier using mineral trioxide aggregate (MTA), and regenerative endodontic procedures. Each of these treatment approaches has its own advantages and disadvantages. This review provides a comprehensive overview of current treatment options for the clinical management of immature permanent teeth with open apices.

Keywords: *Apexification, Calcium hydroxide, Mineral trioxide aggregate, Regenerative endodontics, Necrotic immature permanent tooth*

ÖZ

Gelişimi tamamlanmamış daimi dişlerde pulpa nekrozu, kök gelişiminin durmasına neden olmaktadır. Bu tür dişlerde pulpa nekrozunun gelişiminde genellikle çürükler veya travmalar gibi etmenler rol oynamaktadır. Kök gelişimi tamamlanmamış açık apeksli dişlerin kök kanal tedavileri, klinik yönetim açısından çeşitli zorluklar içermektedir. Özellikle kanal preparasyonu ve dolgusu bu tür vakalarda özel dikkat gerektirmektedir. Bu tip dişlerde geleneksel kök kanal tedavisi, apeksifikasyon, mineral trioksit agregat (MTA) ile apikal bariyer oluşturma ve rejeneratif endodontik prosedürler gibi farklı tedavi seçenekleri uygulanabilmektedir. Bu tedavi yaklaşımlarının her birinin avantajları ve dezavantajları bulunmaktadır. Bu derlemede, kök gelişimi tamamlanmamış açık apeksli daimi dişlerin klinik yönetiminde güncel tedavi seçenekleri ayrıntılı bir şekilde ele alınmaktadır.

Anahtar Kelimeler: *Apeksifikasyon, Kalsiyum hidroksid, Mineral trioksid agregat, Rejeneratif Endodonti, Nekrotik immatür daimi diş*

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Root canal treatment aims to eliminate infected tissue and debris, shape and disinfect root canals, and achieve a three-dimensional, hermetic seal. Although most endodontic cases are predictable and manageable, treating necrotic, immature permanent teeth presents significant clinical challenges due to incomplete root development and inadequate crown-to-root ratios.[1] The complexities arise from thin, divergent dentin walls and an open apex, which hinder effective canal preparation and compromise apical sealing.[1] Additionally, these teeth are more susceptible to root fractures under occlusal forces due to fragile dentin walls.[1]

This review explores the etiologies of pulp necrosis in immature permanent teeth, including trauma, dental caries, and anomalies.[2] It examines evolving treatment modalities, ranging from traditional apexification to modern regenerative endodontic procedures. The review aims to provide updated insights into the clinical management of these challenging cases.

Etiology of Pulp Necrosis in Immature Permanent Teeth

Pulp necrosis in immature permanent teeth disrupts the natural process of root development, leaving the tooth structurally compromised. The two primary causes of pulp necrosis in these cases are caries and trauma.[3]

- *Caries:* is a complex, multifactorial disease that triggers inflammation in the pulp tissue through bacterial invasion and the release of harmful by-products.[3] If left untreated, this inflammatory response can progress to pulp necrosis. The condition is exacerbated by the inability of immature teeth to mount an effective defense due to their underdeveloped dentinal walls.
- *Trauma:* Traumatic injuries, occurring between the ages of 8 and 10, are particularly significant because root development of permanent teeth is still incomplete.[1, 3] During this critical developmental phase, damage to the vascular supply disrupts pulpal circulation. Without sufficient revascularization, the pulp tissue becomes necrotic, leading to a complete cessation of root development.

If pulp pathology affects teeth with open apices, root maturation is abruptly halted. Consequently, these teeth present wide canals, fragile dentin walls, and open apices—sometimes exhibiting a 'blunderbuss' appearance. This unique morphology complicates biomechanical preparation and hinders effective apical closure.[4]

Types of Open Apices

Open apices can be categorized into two distinct types: blunderbuss and non-blunderbuss.[4]

- Blunderbuss Apices: are characterized by divergent canal walls that widen buccolingually, creating a funnel-shaped apex that is broader than the coronal part of the canal. According to the American Association of Endodontists (AAE) Glossary of Endodontic Terms, a blunderbuss canal is defined as an underdeveloped root with an apical diameter that exceeds the coronal diameter.[5] This anatomical configuration presents significant challenges in achieving an apical seal due to its irregular shape and size.
- Non-Blunderbuss Apices: In contrast, non-blunderbuss apices feature canal walls that are either parallel or subtly tapered. The apex remains wide but assumes a more regular shape, such as cylindrical, conical, or convergent.[4] These apices are generally easier to manage during endodontic treatment because of their more predictable morphology.

Cvek categorized root development into five stages based on the width of the apical foramen and root length.[6] This classification provides a systematic approach to assess the maturation of permanent teeth and guides endodontic treatment decisions, particularly in immature teeth with open apices.

Five Stages of Root Development

Stage I: Teeth with wide, divergent apical opening and have less than half of the expected final root length. These teeth exhibit minimal root elongation and significant structural vulnerability due to thin dentinal walls.

Stage II: Teeth with wide, divergent apical opening and have approximately half of the expected final root length. While slightly more developed than Stage I, these teeth still lack sufficient root length and thickness to ensure structural stability.

Stage III: Teeth with wide, divergent apical opening and have about two-thirds of the expected final root length. Although closer to full maturation, the apical closure remains incomplete, necessitating careful endodontic management.

Stage IV: Teeth with a wide, open apical foramen and nearly complete root length. At this stage, the root is almost fully developed, with the apical foramen remaining open but narrowing as maturation continues.

Stage V: Teeth with a closed apical foramen and fully developed root length. These teeth exhibit complete root maturation, with thick dentinal walls and a closed apex, providing optimal structural integrity and resistance to fracture.

Root Development and Potential Complications

Root development begins after the formation of enamel and dentin, reaches the cementoenamel junction (CEJ) and continues for 3 to 4 years following tooth eruption.[7] During this critical period, the Hertwig's epithelial root sheath directs the elongation and maturation of the root. However, if this structure is damaged—due to trauma, caries, or other pathological conditions—pulp necrosis may occur, potentially halting root apex development. As a result, the affected tooth remains immature, presenting a blunderbuss canal anatomy characterized by a wide apical opening and thin dentinal walls.[1] This unique morphology poses significant challenges for endodontic treatment, particularly in achieving effective apical sealing and preventing root fractures.[1]

An open apex is commonly associated with young permanent teeth that experience trauma during the early stages of root development.[8] Such injuries can disrupt the vascular supply to the pulp, leading to necrosis and premature cessation of root formation. Consequently, the tooth remains underdeveloped with wide canals and fragile walls, increasing its susceptibility to fracture and complicating endodontic management.[8] However, an open apex is not exclusively linked to immature teeth. In some cases, it can also occur in fully developed teeth due to specific pathological conditions, including:

- *External Inflammatory Root Resorption:* Resulting from chronic periapical inflammation or trauma.
- *Iatrogenic Over-Preparation:* Excessive instrumentation during endodontic procedures may weaken the apical region.
- *Root Resection:* Surgical removal of the apical portion of the root. [9-11]

These conditions disrupt the apical closure, leading to an open apex that requires specialized endodontic techniques to achieve effective sealing and long-term clinical success.

Clinical Challenges in Endodontic Treatment of Teeth with Open Apices

The endodontic management of teeth with open apices involves several complex clinical challenges due to their unique anatomical structure. These challenges require meticulous planning and precise execution to ensure successful treatment outcomes.

1. Determination of Working Length

Accurately establishing the working length in teeth with open apices is particularly challenging due to the absence of a natural apical constriction. If the working length is inaccurately determined, there is a significant risk of over-instrumentation, leading to the extrusion of irrigation solutions, intracanal medicaments, or root canal filling materials beyond the apex. This accidental extrusion may cause persistent periapical inflammation and increase the likelihood of postoperative pain.[12]

To minimize the risk of over-preparation, it is recommended to use electronic apex locators in conjunction with radiographic evaluation to determine the precise working length.[13] The combined use of these diagnostic tools enhances accuracy, reduces the risk of overfilling, and ensures adequate cleaning and shaping without compromising the periapical tissues.

2. Cleaning and Shaping of Root Canals

Teeth with open apices are inherently more susceptible to root fractures due to their thin and fragile dentinal walls. This structural weakness presents a significant challenge when performing conventional cleaning and shaping procedures, as:[14]

- Excessive instrumentation can further weaken the dentinal walls, increasing the risk of vertical root fractures.
- Mechanical preparation is particularly challenging, as it requires delicate handling to avoid unintentional damage to the already fragile root structure.[14]

To address these challenges, clinicians should adopt **minimally invasive cleaning and shaping techniques** that prioritize **chemical disinfection** over aggressive mechanical instrumentation. This approach may reduce the risk of fracture while ensuring thorough debridement of the root canal system.

3. Obturation of Root Canals

The blunderbuss canal anatomy frequently observed in immature teeth poses considerable difficulties in achieving an optimal three-dimensional obturation. Despite these challenges, adequate root canal obturation remains a critical step in the endodontic treatment process. In fact, studies indicate that approximately 60% of endodontic failures are directly linked to inadequate root canal filling.[15]

Treatment Options for Immature, Non-vital Permanent Teeth with Open Apices

The primary objective of treating immature, non-vital permanent teeth with open apices is to achieve healing of periapical pathology, resolution of clinical symptoms, continued root development with apical closure, and restoration of functional pulp vitality.[16] Preserving immature permanent teeth is crucial for both functional and aesthetic reasons. These teeth play a vital role in:

- *Maintaining Occlusal Function:* Ensuring proper alignment and function within the dental arch.

- *Supporting Facial Aesthetics:* Contributing to facial profile and symmetry, particularly during craniofacial growth.

Furthermore, implant placement is generally contraindicated in young patients until craniofacial growth is complete.[16] Therefore, retaining immature permanent teeth becomes even more critical to prevent space loss and maintain alveolar bone integrity.

Due to the thin and fragile dentin walls characteristic of immature teeth, conventional root canal cleaning and shaping techniques may further weaken the root structure. Therefore, the disinfection of infected root canals in these cases primarily relies on irrigation solutions and intracanal medicaments. [17]

Evolution of Treatment Approaches for Immature, Infected Permanent Teeth

In the past, the treatment of immature, infected permanent teeth involved techniques that focused on achieving adequate obturation without promoting continued root development. These conventional methods included the placement of large gutta-percha fillings or the roll-cone gutta-percha technique, with the root canal filling materials positioned short of the apex, or by performing periapical surgery. [18]

However, these traditional approaches were limited by the absence of an apical barrier, which compromised the quality of the apical seal and increased the risk of microleakage.[13] As a result, these techniques have been largely replaced by more advanced methods that provide predictable outcomes and improved long-term success.[13] Currently, there are three main treatment modalities for immature permanent teeth with infected root canal systems and open apices:

- Apexification with calcium hydroxide ($Ca(OH)_2$),
- Apical barrier formation using mineral trioxide aggregate (MTA), and
- Regenerative endodontic procedures.

Apexification

Apexification is defined as "the process of inducing a calcified barrier in the apical region of an immature root with a necrotic pulp or facilitating the continued apical development of an incompletely formed root."[5] This procedure involves biomechanical canal debridement beyond the apex, followed by the placement of a biocompatible material to induce a hard tissue barrier and facilitate root canal obturation by forming an apical barrier. [19,20]

Calcium hydroxide remains the gold standard for apexification due to its potent antibacterial properties and ability to stimulate the formation of an apical hard tissue barrier.[20-22] This material plays a crucial role in endodontics by creating an environment that supports mineral deposition and prevents microbial proliferation within the root canal system. The apical hard tissue barrier formed by calcium hydroxide is commonly described as a cap, bridge, or inward-growing wedge. It consists of multiple layers of necrotic and mineralized tissues, which contribute to its structural integrity. However, this barrier is often porous and incomplete, making it susceptible to microleakage. Histological studies reveal that it may contain cementum, dentin, bone, or a specialized form of mineralized tissue referred to as 'osteodentin. [19,20]

Research suggests that in immature teeth with infected pulp and a compromised Hertwig's epithelial root sheath, viable cementoblasts and undifferentiated fibroblasts within the periapical tissues and periodontal ligament play a crucial role in apexification.[19] These cells are thought to differentiate and contribute to the formation of the apical hard tissue barrier, facilitating root development despite the loss of normal Hertwig's epithelial function.[19] Apexification with $Ca(OH)_2$ has been extensively studied in endodontics and remains a widely accepted and reliable treatment approach.[18] It has demonstrated consistent success in inducing mineralized tissue deposition, creating an effective apical barrier to prevent further resorption and reinfection. However, treatment duration and variability in barrier integrity remain key considerations when selecting this approach.[18] Table 1 outlines the indications and contraindications for apexification, highlighting the clinical scenarios where this technique is most beneficial and where alternative strategies may be preferable.

Table 1: Criteria to Consider When Determining the Indication for Apexification Treatment.

Indications for Apexification	Contraindications for Apexification
Necrotic/infected pulp in an immature tooth **(+)**	Presence of purulent drainage from canals
No spontaneous pain, uncontrolled bleeding, or percussion sensitivity	Presence of persistent long-term pain
Root length ≥ ½ of its expected final length **(+)**	Presence of extremely short root(s)
No evidence of horizontal or vertical root fracture	Periodontal damage extending near the gingival margin
No radiographic signs of ankylosis	Presence of vital pulp tissue
Tooth is restorable **(+)**	
Presence of periapical radiolucency	

Mechanism of Action and Limitations of Calcium Hydroxide in Apexification

The biological effects of $Ca(OH)_2$ are primarily attributed to the dissociation of calcium and hydroxyl ions, which significantly influence the periapical environment. Upon application, $Ca(OH)_2$ elevates the local pH to approximately 12.5, creating an alkaline environment that plays a critical role in endodontic healing. [23]

Its high alkalinity neutralizes lactic acid produced by osteoclasts in the periapical region, effectively inhibiting demineralization and halting further bone resorption.[24] Moreover, $Ca(OH)_2$ stimulates alkaline phosphatase activity, which is essential for the initiation and regulation of hard tissue formation. Additionally, the gradual release of calcium ions has been shown to activate growth factors necessary for mineralization and tissue repair. [25]

While calcium hydroxide remains a cornerstone in apexification, its use presents several notable limitations that must be considered in clinical decision-making:

- Limited Root Development: The hard tissue barrier induced by $Ca(OH)_2$ forms only at the apical region, leaving the root canal walls thin and short. As a result, no further root elongation or structural reinforcement occurs, potentially compromising long-term tooth viability.[19-21]
- Impact on Regenerative Potential: Due to its high pH, $Ca(OH)_2$ has been suggested to damage cells with regenerative capacity that might otherwise contribute to continued root development or pulp regeneration.[19]
- Structural Weakening of Dentin: Prolonged exposure to calcium hydroxide has been associated with increased dentin brittleness, primarily due to its hygroscopic and proteolytic effects. This structural degradation raises the risk of root fractures, with studies indicating a 50% reduction in fracture resistance after one year of intracanal $Ca(OH)_2$ application. [19,20,26,28]
- Extended Treatment Duration: One of the major drawbacks of calcium hydroxide apexification is the need for frequent medicament changes and an often-prolonged treatment course. The duration varies depending on factors such as patient age, periradicular radiolucency, and apical width.[20,29] Reports indicate that the time required for apical barrier formation ranges between 3 and 24 months, with an average duration of 12 months.[22,26]

The prolonged treatment duration and multiple required appointments pose significant challenges in clinical practice. Extended therapy not only reduces patient compliance but also complicates follow-up care, making long-term monitoring more difficult. Additionally, prolonged exposure to potential coronal leakage heightens the risk of bacterial reinfection, potentially compromising treatment success.[20,26]

Given these limitations, MTA has emerged as a more favourable alternative to calcium hydroxide in apexification. Its superior sealing ability, biocompatibility, and faster barrier formation have led to its increasing adoption in endodontic practice.[30, 31] MTA addresses many of the drawbacks associated with calcium hydroxide, offering a more predictable and efficient solution for managing immature necrotic teeth.

Apical Barrier Technique

The apical barrier technique is defined as the nonsurgical condensation of a biocompatible material at the apical end of the root canal.[30] The primary objective of this method is to establish an artificial apical plug, enabling predictable root canal obturation without relying on the induction of natural apical closure. By providing a stable apical seal, this approach minimizes the risk of extrusion and enhances long-term treatment success. Developed to address the limitations of traditional calcium hydroxide apexification, the apical barrier technique has gained widespread acceptance, particularly with the use of MTA as the preferred material. MTA's excellent biocompatibility, sealing properties, and ability to stimulate hard tissue formation make it the material of choice for this procedure. In addition to MTA, various alternative biomaterials have been explored for apical barrier formation, including tricalcium phosphate, calcium hydroxide, freeze-dried bone, dentin derivatives, and bioceramic materials.[31-34] These materials aim to optimize apical healing while providing a reliable scaffold for mineralization and tissue regeneration.

Mineral Trioxide Aggregate (MTA) in Apical Barrier Technique

MTA is a hydrophilic biomaterial that forms a colloidal gel upon mixing with water.[35] Initially, MTA exhibits a pH of 10.2, which gradually rises to 12.5 during the setting phase and remains stable for up to three hours.[36,37] This highly alkaline environment contributes to MTA's antibacterial properties, excellent biocompatibility, and capacity to stimulate hard tissue formation. [26]

In the apical barrier technique, thorough chemomechanical disinfection of the root canal system is performed before material placement. To enhance antimicrobial action, intracanal dressing with $Ca(OH)_2$ is applied for at least one week. At the following appointment, the $Ca(OH)_2$ dressing is removed, the canals are carefully dried, and a 3-4 mm thick MTA plug is compacted at the apical end of the canal. Once the MTA sets, the remaining root canal space is obturated

using gutta-percha and a root canal sealer, ensuring a complete and biocompatible seal.

MTA has emerged as the material of choice in the apical barrier technique, offering several advantages over calcium hydroxide:[19]

- Superior Sealing Properties: MTA forms a highly effective apical seal, minimizing microleakage and reducing the risk of reinfection. Additionally, it exhibits the ability to set in a moist environment, ensuring a stable and predictable barrier even under challenging clinical conditions. [34,38]
- Biocompatibility and Safety: Research indicates that MTA does not induce adverse tissue reactions when extruded beyond the apex. Moreover, it has been shown to support periapical healing rather than compromising it, making it a safer alternative for apexification procedures.[38]

Limitations of MTA in Apical Barrier Technique

Despite its advantages, the apical barrier technique with MTA shares a fundamental limitation with traditional apexification—it does not support continued root development or improve the crown-to-root ratio.[38,39] As a result, teeth treated with this approach may remain structurally compromised, particularly in cases where root formation is incomplete.

Additionally, studies indicate that in teeth with short roots and thin dentinal walls, the risk of root fracture persists even after MTA treatment. However, this risk is believed to be lower compared to calcium hydroxide-treated teeth, where prolonged exposure may further weaken the dentin structure.[2]

Regenerative Endodontics

Regenerative endodontic treatment is based on three core principles of tissue engineering:

I. Identification of appropriate stem or progenitor cell sources,

II. Delivery of growth factors to guide cellular differentiation, and

III. Establishment of a 3D scaffold that supports sustained cellular proliferation and specialization.[40]

The apical papilla and periapical tissues of developing permanent teeth serve as key reservoirs for stem cells, offering a critical source for tissue regeneration.[41-43] Pulp revitalization is primarily dependent on the differentiation capacity of residual pulpal and periodontal stem cells.[44,45]

This process leads to the formation of a vascularized, connective tissue-rich living matrix, which gradually occupies the pulp space. Within this matrix, stem cells differentiate into odontoblast-like cells, initiating the deposition of hard tissue with characteristics that remain incompletely defined.[16] The outcome of this biological cascade represents a significant advancement in regenerative dentistry, offering the potential for functional root development and continued dentin formation, distinguishing it from traditional apexification approaches.

Revascularization in Regenerative Endodontics

Revascularization has emerged as a groundbreaking approach for managing necrotic, immature permanent teeth, offering a biologically driven alternative to traditional apexification. Traditionally, apexification was the treatment of choice for such cases, aiming to create an apical barrier to facilitate obturation. However, revascularization represents a superior approach, as it actively promotes continued root development rather than merely inducing apical closure.[16,46]

Unlike conventional techniques, revascularization stimulates apical healing while preserving the tooth's natural potential for growth. This biological process results in progressive apical narrowing, further root elongation, and dentinal wall thickening, ultimately leading to the formation of a natural, fully developed apex. [16,46] By fostering these structural improvements, revascularization significantly enhances long-term tooth prognosis, reinforcing its role as a preferred modality in regenerative endodontics.

Significance of Apical Foramen Width in Regenerative Endodontics

An essential factor influencing the success of regenerative endodontic treatment is the size of the apical foramen. Clinical evidence suggests that immature permanent teeth with an apical foramen diameter between 1.1 mm and 5 mm are the most ideal candidates for this approach.[47-50]

When the apical foramen is narrower, the restricted blood flow to the root tip may impede tissue regeneration and compromise clinical outcomes.[21,48] Adequate vascularization is crucial for the delivery of essential growth factors and the recruitment of stem/progenitor cells, both of which are fundamental to successful pulp-dentin regeneration. For optimal case selection and treatment planning, practical guidelines, contraindications, and key considerations for regenerative endodontics are summarized in Table 2.

Table 2: Key Considerations in Regenerative Endodontic Treatment Applications.

Considerations	Clinical Implications
Fully developed teeth generally have a better prognosis with conventional endodontic treatment	Before opting for regenerative endodontics, it should be evaluated whether an immature necrotic permanent tooth can be salvaged using apexification or non-surgical conventional root canal treatment
Inadequate root canal disinfection increases the risk of infection spreading to adjacent tissues	Proper chemo-mechanical preparation is essential to minimize this risk
Undiluted disinfectants should not be used (e.g., sodium hypochlorite)	Special care should be taken to prevent leakage and apical extrusion
Only necrotic or infected tissue inside the canal should be removed	Excessive instrumentation should be avoided to prevent weakening of thin dentinal walls and to minimize the risk of fracture
If apical bleeding does not fill the entire root canal space, revascularization may fail	Achieving adequate apical bleeding is a critical step in the regenerative process
Donor blood should not be introduced into the root canal, and unanchored exogenous stem cells should not be added due to significant health risks	The use of unproven or experimental techniques may compromise treatment success and patient safety
MTA should not be placed below the cemento-enamel junction (CEJ)	Positioning MTA too apically may prevent dentin regeneration at structurally weak fracture-prone areas
Minocycline should not be used for root canal disinfection to prevent tooth discoloration	Alternative antibiotics or antimicrobial agents should be considered
The cervical third of immature tooth roots, which is most prone to fracture, should be reinforced with composite and/or fiber posts	Restorative measures should be implemented to enhance long-term structural integrity

CONCLUSION

The management of necrotic and infected immature permanent teeth with open apices has undergone a significant transformation, shifting from traditional apexification techniques with calcium hydroxide or MTA to regenerative endodontic procedures. The driving force behind this paradigm shift is the ability of regenerative therapy to facilitate continued root development, offering a biological advantage over conventional methods. For cases where root length and dentinal thickness are insufficient, regenerative endodontic therapy is generally regarded as the preferred approach. However, patients should be fully informed about the possibility of unpredictable outcomes. In scenarios where regenerative treatment is not feasible, the MTA apical barrier technique serves as a viable alternative. Conversely, for cases with adequate root dimensions, both MTA apexification and traditional root canal treatment remain reliable options. A precise differential diagnosis is essential when determining the most appropriate intervention, especially among various treatment modalities, including apexogenesis, conventional root canal therapy, regenerative endodontics, vital pulp therapies (e.g., Cvek partial pulpotomy), and apexification. The clinical decision-making process for selecting the optimal treatment approach is outlined in Figure 1. [49]

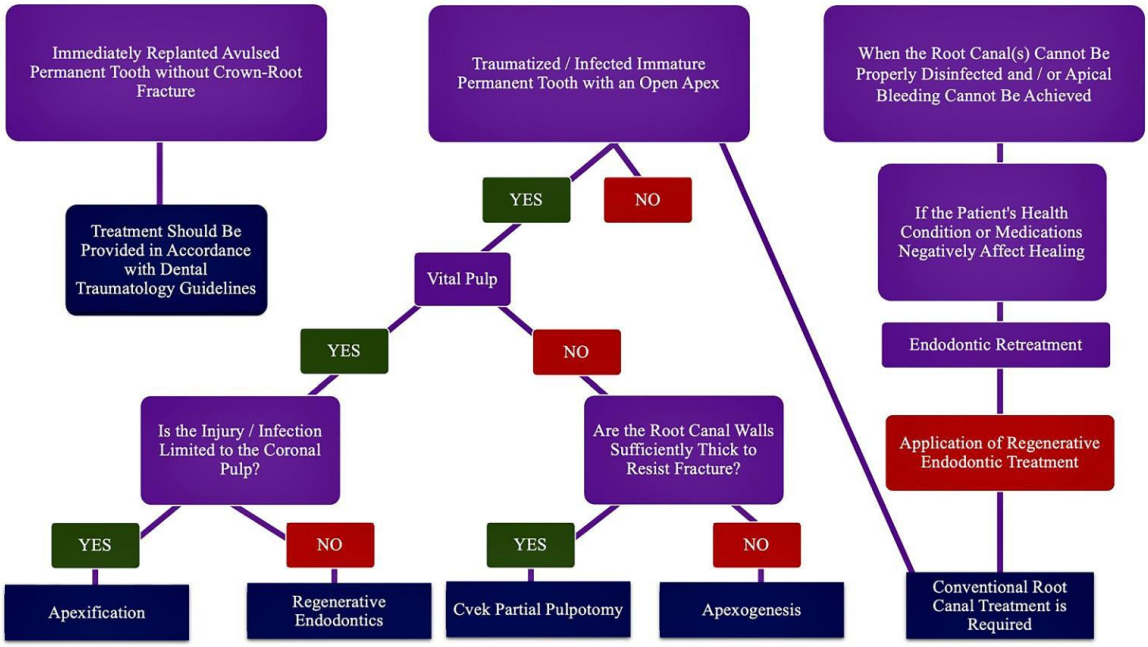

Figure 1: A flowchart assisting in the decision-making process for appropriate endodontic treatment options in immature permanent teeth.[49]

Despite the growing interest in regenerative endodontic procedures, the current lack of randomized clinical trials and long-term clinical data presents a challenge in defining standardized case selection criteria. Therefore, further well-designed clinical studies are necessary to establish evidence-based guidelines for the predictable and effective application of regenerative endodontic therapy.

REFERENCES

1. Rafter M. Apexification: a review. *Dent Traumatol* 2005; 21: 1–8.
2. Chen X, Bao ZF, Liu Y, Liu M, Jin XQ, Xu XB. Regenerative endodontic treatment of an immature permanent tooth at an early stage of root development: a case report. *J Endod.* 2013; 39: 719-22.
3. Mohammadi Z. Strategies to manage permanent non-vital teeth with open apices: a clinical update. *Int Dent* J 2011; 61: 25–30.
4. Gupta R, Tomer AK, Cecilia LL. Challenges and Treatment Strategies of Open Apex. *IOSR-JDMS* 2021; 20: 20-24.
5. American Association of Endodontists, Glossary of endodontic terms.10th Ed., Chicago 2020.
6. Cvek M. Prognosis of luxated non-vital maxillary incisors treated with calcium hydroxide and filled with gutta-percha: a retrospective clinical study. *Endod Dent Traumatol* 1992; 8:45-55.
7. Holland GR, Trowbridge HO, Rafter M, Torbinejad M, Walton RE, Charles F. Protecting the pulp, preserving the apex. In: Torbinejad M, Walton RE. Endodontics, principles and practice, 4th Ed., Saunders, ABD. 2008, 26-34.
8. Flanagan TA. What can cause the pulps of immature, permanent teeth with open apices to become necrotic and what treatment options are available for these teeth. *Aust Endod J* 2014; 40:95-100.
9. Cotti E, Lusso D, Dettori C. Management of apical inflammatory root resorption: report of a case. *Int Endod J* 1998; 31:301–44.
10. Trope M. Root resorption due to dental trauma. *Endod Topics* 2002; 1:79–100
11. Gutiérrez JH, Brizuela C, Villota E. Human teeth with periapical pathosis after over instrumentation and overfilling of the root canals: a scanning electron microscopic study. *Int Endod J* 1999; 32:40–8.
12. Wikström A, Brundin M, Romani Vestman N, Rakhimova O, Tsilingaridis G. Endodontic pulp revitalization in traumatized necrotic immature permanent incisors: early failures and long-term outcomes-a longitudinal cohort study. *Int Endod J* 2022; 55: 630–645.
13. ElAyouti A, Weiger R, Löst C. The ability of root ZX apex locator to reduce the frequency of overestimated radiographic working length. *J Endod.* 2002; 28:116-119
14. Seghi RR, Nasrin S, Draney J, Katsube N. Root fortification. *J Endod* 2013; 39: S57-62.

15. Ingle JI, Bakland LK. Endodontics, 5th Ed., BC Decker, Hamilton, England, 2002, 1–46.
16. Hargreaves KM, Diogenes A, Teixeira FB. Treatment options: biological basis of regenerative endodontic pro- cedures. *J Endod* 2013; 39: S30–43.
17. Lovelace TW, Henry MA, Hargreaves KM, Diogenes A. Evaluation of the delivery of mesenchymal stem cells into the root canal space of necrotic immature teeth after clinical regenerative endodontic procedure. *J Endod* 2011; 37: 133–8.
18. Gaitonde P, Bishop K. Apexification with mineral trioxide aggregate: an overview of the material and technique. *Eur J Prosthodont Restor Dent* 2007; 15: 41–5.
19. Aggarwal V, MIglani S, Singla M. Conventional apexification and revascularization induced maturogenesis of two non-vital, immature teeth in same patient: 24 months follow up of a case. *J Conserv Dent* 2012; 15: 68–72.
20. Jyothi M. Management of immature teeth – a paradigm shift from apexification to apexogenesis. *Ann Essences Dent* 2012; 3: 34–8.
21. Chen MYH, Chen KL, Chen CA, Tayebaty F, Rosenberg P, Lin LM. Responses of immature permanent teeth with infected necrotic pulp tissue and apical periodontitis/abscess to revascularization procedures. *Int Endod J* 2012; 45: 294–305.
22. Thomson A, Kahler B. Regenerative endodontics – biologically-based treatment for immature permanent teeth: a case report and review of the literature. *Aust Dent J* 2010; 55: 446–52.
23. Mustafa M, Saujanya KP, Jain D, Sajjanshetty S, Arun A, Uppin L, et al. Role of calcium hydroxide in endodontics: a review. Glob J Med Public Health. 2012; 1: 2-5.
24. Tronstad L, Andreasen JO, Hasselgren G, Kristerson L, Riis I. pH changes in dental tissues after root canal filling with calcium hydroxide. J Endo. 1981; 7: 17-21
25. Koh ET, Torabinejad M, Pitt Ford TR, Brady K, McDonald F. Mineral trioxide aggregate stimulates a biological response in human osteoblasts. J Biomed Mater Res. 1997; 37: 432-439
26. McTique D, Sumbramanian K, Kumar A. Management of immature permanent teeth with pulpal necrosis: a case series. *Pediatr Dent* 2013; 35: 55–60.
27. Hargreaves KM, Giesler T, Henry M, Wang Y. Regeneration potential of the young permanent tooth: what does the future hold? *Pediatr Dent* 2008; 30: 253–60.
28. Andreasen JO, Farik B, Munksgaard EC. Long-term calcium hydroxide as a root canal dressing may increase risk of root fracture. *Dent Traumatol* 2002; 18: 134–7.
29. Shabahang S. Treatment options: apexogenesis and apexification. *Pediatr Dent* 2013; 35: 125–8.
30. Hiremath H, Gada N, Kini Y, Kulkarni S, Yakub SS, Metgud S. Single-step apical barrier placement in immature teeth using mineral trioxide aggregate and management of periapical inflammatory lesion using platelet-rich plasma and hydroxyapatite. *J Endod* 2008; 34: 1020–1024.
31. Harbert H. One step apexification without calcium hydroxide. *J Endod* 1996; 22:690–2.
32. Schumacher JW, Rutledge RE. An alternative to apexification. *J Endod* 1993; 19:529-31.
33. Saxena P, Gupta SK, and Newaskar Biocompatibility of root-end filling materials, recent update. *Restor Dent Endod* 2013; 38:119–127.
34. Tselnik M, Baumgartner J, Marshall J. Bacterial leakage with mineral trioxide aggregate or a resin-modified glass ionomer used as a coronal barrier. *J Endod* 2004; 30: 782–4.
35. Macwan C, Deshpande A. Mineral trioxide aggregate (MTA) in dentistry: A review of literature. J Oral Res Rev. 2014; 6: 71.
36. Torabinejad M, Hong CU, McDonald F, Ford TP. Physical and chemical properties of a new root-end filling material. J Endo. 1995; 21: 349-353.
37. Rao A, Rao A, Shenoy R. Mineral trioxide aggregate-a review. J Clin Pediatr Dent. 2009; 34: 1-8.
38. Cehreli Z, Sara S, Uysal S, Turgut MD. MTA apical plugs in the treatment of traumatized immature teeth with large periapical lesions. *Dent Traumatol* 2011; 27: 59–62.
39. Nosrat A, Homayounfar N, Oloomi K. Drawbacks and unfavourable outcomes of regenerative endodontic treat- ments of necrotic immature teeth: a literature review and report of a case. *J Endod* 2012; 38: 1428–34.
40. Alongi DJ, Yamaza T, Song Y, et al. Stem/progenitor cells from inflamed human dental pulp retain tissue regeneration potential. *Regen Med* 2010; 5: 617–631.
41. Ding RY, Cheung GS, Chen J, Yin XZ, Wang QQ, Zhang CF. Pulp revascularization of immature teeth with apical periodontitis: a clinical study. *J Endod* 2009; 35: 745–749.
42. Thibodeau B, Teixeira F, Yamauchi M, Caplan DJ, Trope M. Pulp revascularization of immature dog teeth with apical periodontitis. *J Endod* 2007; 33: 680–689.
43. Kontakiotis EG, Filippatos CG, Tzanetakis GN, Agrafioti A. Regenerative endodontic therapy: a data analysis of clinical protocols. *J Endod* 2015; 41: 146–154.
44. Torabinejad M, Corr R, Buhrley M, Wright K, Shabahang S. An animal model to study regenerative endodontics. *J Endod* 2011; 37: 197–202.

45. Nosrat A, Seifi A, Asgary S. Regenerative endodontic treatment (revascularization) for necrotic immature permanent molars: a review and report of two cases with a new biomaterial. *J Endod* 2011; 37: 562–567.
46. Petrino JA. Revascularization of necrotic pulp of immature teeth with apical periodontitis. *Northwest Dent* 2007; 86: 33–35.
47. Conde MCM, Chisini LA, Sarkis-Onofre R, Schuch HS, Nör JE, Demarco FF. A scoping review of root canal revascularization: relevant aspects for clinical success and tissue formation. *Int Endod J* 2017; 50: 860-874.
48. Garcia-Godoy F, Murray PE. Recommendations for using regenerative endodontic procedures in permanent immature traumatized teeth. *Dent Traumatol* 2012; 28: 33–41.
49. Kling M, Cvek M, Mejare I. Rate and predictability of pulp revascularization in therapeutically reimplanted permanent incisors. *Endod Dent Traumatol* 1986; 2:83-9.
50. Murray PE. Review of guidance for the selection of regenerative endodontics, apexogenesis, apexification, pulpotomy, and other endodontic treatments for immature permanent teeth. *Int Endod J* 2023; 56: 188-199.