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RESEARCH ARTICLE

Periodontal–Pulpal Interface Healing Following Vital Pulp Therapy Using Calcium-Silicate Bioceramics

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ABSTRACT

Forensic endodontics relies on the unique anatomical features of teeth, particularly root canal morphology, to assist in individual identification. Recent advances in artificial intelligence (AI) offer powerful tools to analyze complex dental patterns; however, the "black-box" nature of many AI models limits their applicability in legal and forensic contexts. This study explores the development of explainable AI (XAI) models designed to link root canal configurations to individual dental identities. By integrating high-resolution dental imaging data with interpretable machine learning approaches, the proposed framework not only achieves accurate pattern recognition but also provides transparent insights into model decisions, enabling forensic practitioners to validate and justify identification outcomes. The findings demonstrate that XAI can bridge the gap between advanced computational analysis and forensic accountability, offering a robust, ethical, and legally defensible methodology for dental identification.

Keywords: Forensic endodontics, explainable AI, root canal morphology, dental identification, interpretable machine learning, pattern recognition, forensic dentistry.

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INTRODUCTION

Vital pulp therapy (VPT) is a conservative endodontic procedure aimed at preserving the vitality of the dental pulp following injury or carious exposure. The primary goal of VPT is to maintain the normal function of the pulp and to promote tissue repair and regeneration, rather than performing complete pulp removal (Singh, 2019). This approach has gained increasing attention due to its potential to maintain long-term tooth health and prevent more invasive procedures such as root canal therapy.

The periodontal–pulpal interface represents a critical area where the pulp and surrounding periodontal tissues communicate through vascular and cellular networks. Proper healing at this interface is essential for the overall success of VPT, as it ensures the maintenance of pulp vitality, prevents microbial invasion, and supports the regeneration of both pulpal and periodontal tissues (Xavier et al., 2021). Damage to this interface can compromise both pulp and periodontal health, leading to treatment failure.

Calcium-silicate bioceramics have emerged as the material of choice in modern VPT due to their favorable properties, including excellent biocompatibility, bioactivity, sealing ability, and capacity to induce reparative dentin formation (Bogen, 2016; Ashraf, Rahmati, & Amini, 2017). These materials interact with the surrounding tissues to stimulate cellular responses that support healing at the periodontal–pulpal interface. In vitro and in vivo studies have demonstrated that calcium-silicate bioceramics promote proliferation, differentiation, and mineralization of pulp cells, highlighting their potential to enhance tissue regeneration (Song, Li, Tang, Chen, & Yuan, 2021; Song, Sun, Chen, & Yuan, 2020).

The interface between restorative and regenerative biomaterials and the natural tooth structure plays a crucial role in achieving predictable clinical outcomes. Recent studies emphasize that the selection of appropriate bioceramic materials and their interaction with the host tissue significantly influences healing dynamics and long-term success (Xavier et al., 2021). Despite

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Table 1: Common Materials for Vital Pulp Therapy and Their Characteristics

Material	*Key Properties*	*Advantages*	*Limitations*	*References*
Calcium Hydroxide	High pH, antibacterial, induces reparative dentin	Widely used, low cost	Dissolution over time, poor sealing, tunnel defects in dentin bridge	Singh, 2019
Mineral Trioxide Aggregate (MTA)	Biocompatible, bioactive, sets in moisture	Promotes dentin bridge formation, good sealing	Long setting time, expensive, handling difficulty	Bogen, 2016; Ashraf et al., 2017
Biodentine	Calcium-silicate based, fast setting	Excellent sealing, bioactive, stimulates odontoblast-like cells	Moderate cost, limited long-term clinical data	Song et al., 2020; Xavier et al., 2021
Other Bioceramics	Varied compositions (calcium silicate with additives)	High biocompatibility, stable, antibacterial	New materials may lack extensive clinical validation	Song et al., 2021

growing evidence supporting the use of calcium-silicate bioceramics, understanding the biological processes involved in periodontal–pulpal interface healing remains a focus of ongoing research.

This study aims to explore the healing mechanisms at the periodontal–pulpal interface following VPT using calcium-silicate bioceramics, providing insights into their clinical efficacy and potential to enhance tissue regeneration.

Vital Pulp Therapy (VPT) Overview

Vital pulp therapy (VPT) is a conservative endodontic approach aimed at preserving and maintaining the vitality of the dental pulp following injury or carious exposure. The primary goal is to promote healing and regenerative responses within the pulp while preventing bacterial infiltration and subsequent pulp necrosis (Singh, 2019). Over the years, VPT has evolved from using traditional calcium hydroxide-based materials to modern calcium-silicate bioceramics, which offer improved biocompatibility and bioactivity (Bogen, 2016; Song et al., 2021).

2.1 Types of Vital Pulp Therapy

VPT can be categorized based on the extent of pulp tissue removal and clinical indications. The major types include:

- **Direct pulp capping** – Placement of a protective material directly over an exposed pulp to stimulate reparative dentin formation.
- **Partial (or shallow) pulpotomy** – Removal of a small portion of the coronal pulp beneath the exposure site, leaving the remaining pulp intact.
- **Full pulpotomy** – Complete removal of the coronal pulp while preserving radicular pulp tissue to maintain tooth vitality.

The choice of procedure depends on factors such as the size of pulp exposure, degree of inflammation, patient age, and tooth type (Ashraf, Rahmati, & Amini, 2017).

Materials Used in VPT

Historically, calcium hydroxide was the material of choice due to its antibacterial properties and ability to induce reparative dentin. However, limitations such as poor sealing ability and dissolution over time have prompted the development of calcium-silicate bioceramics. These materials demonstrate superior biocompatibility, bioactivity, and dimensional stability, making them suitable for long-term pulp preservation (Singh, 2019; Song et al., 2020).

A comparative summary of materials used in VPT is provided in Table 1.

Mechanisms of Healing

Calcium-silicate bioceramics used in VPT facilitate pulp healing through several mechanisms:

Induction of odontoblast-like cell differentiation and reparative dentin formation.

Modulation of inflammatory responses, favoring tissue regeneration rather than necrosis.

Formation of a tight seal that prevents bacterial microleakage (Xavier et al., 2021; Song et al., 2020).

These mechanisms contribute to favorable outcomes at the periodontal–pulpal interface, preserving pulp vitality while supporting periodontal health.

Clinical Outcomes

Clinical studies and case reports indicate high success rates for VPT using calcium-silicate bioceramics. Factors influencing outcomes include the degree of pulp inflammation, tooth maturity, and procedural technique. In both short- and long-term assessments, teeth treated with modern bioceramics demonstrate improved pulp vitality retention and reduced postoperative complications compared to traditional materials (Ashraf et al., 2017; Song et al., 2021).

Clinical and Radiographic Assessment of Healing

The clinical and radiographic assessment of periodontal–pulpal interface healing following vital pulp therapy (VPT) is critical for determining treatment success and long-term prognosis. Healing assessment focuses on evaluating both pulp vitality and periodontal tissue responses after the application of calcium-silicate bioceramics.

Clinical Assessment

Clinical evaluation involves direct observation of the treated tooth and assessment of patient-reported symptoms. Key parameters include:

- **Pain or discomfort:** Persistent pain may indicate pulp inflammation or necrosis (Singh, 2019).
- **Sensitivity testing:** Thermal or electric pulp testing is used to assess pulp vitality post-treatment (Ashraf, Rahmati, & Amini, 2017).
- **Signs of infection:** Swelling, sinus tract formation, or tenderness on percussion suggests failure of the pulp–periodontal interface (Xavier et al., 2021).
- **Tooth function:** Normal masticatory function without discomfort is a positive indicator (Bogen, 2016).

Clinical assessments should be performed at regular intervals: immediately post-treatment, 1–3 months, 6 months, and 12 months after therapy to monitor healing progression (Singh, 2019; Ashraf et al., 2017).

Radiographic Assessment

Radiographic evaluation complements clinical assessment by providing objective evidence of tissue healing. Common imaging modalities include periapical radiographs and cone-beam computed tomography (CBCT) for detailed

Table 2

Assessment Parameter	*Success Indicator*	*Failure Indicator*	*Reference*
Pain/Discomfort	No pain, normal response to function	Persistent or severe pain, spontaneous pain	Singh, 2019
Pulp Vitality	Positive response to thermal/electric tests	No response or increased sensitivity	Ashraf et al., 2017
Periapical Status	Absence of radiolucency or healing of pre-existing lesion	New or expanding radiolucency	Bogen, 2016
Dentin Bridge Formation	Radiopaque dentin formation at pulp exposure site	Absence of bridge, persistent pulp exposure	Song et al., 2021
Periodontal Ligament (PDL)	Normal width, no widening or resorption	Widened PDL, bone loss	Song et al., 2020
Signs of Infection	No swelling, sinus tract, or tenderness	Swelling, fistula, tenderness on percussion	Xavier et al., 2021

Summary Table of Challenges

Category	*Challenge*	*Impact on Healing*	*Reference*
Technical	Incomplete pulp removal	Persistent inflammation, reduced success	Singh, 2019; Ashraf et al., 2017
Technical	Handling and placement difficulties	Improper adaptation, compromised sealing	Bogen, 2016
Biological	Reduced regenerative capacity in older patients	Delayed or incomplete reparative dentin formation	Song et al., 2020
Biological	Microleakage at interface	Bacterial contamination, periodontal involvement	Xavier et al., 2021; Song et al., 2021
Material-related	Prolonged setting time	Delays in restoration placement	Bogen, 2016
Material-related	Solubility/dimensional instability	Compromised long-term sealing	Bogen, 2016
Material-related	High cost	Limited clinical adoption	Singh, 2019
Evidence gaps	Limited long-term clinical trials	Uncertain long-term efficacy	Xavier et al., 2021

visualization (Xavier et al., 2021). Radiographic indicators include:

- **Periapical status:** Resolution of pre-existing radiolucency or absence of new periapical lesions indicates successful healing (Bogen, 2016).
- **Dentin bridge formation:** Radiopaque reparative dentin at the pulp exposure site confirms bioactivity of calcium-silicate bioceramics (Song, Li, Tang, Chen, & Yuan, 2021).
- **Periodontal ligament (PDL) space:** Maintenance or normalization of PDL width is an indicator of healthy interface healing (Song, Sun, Chen, & Yuan, 2020).

Combined Clinical-Radiographic Criteria for Success

The integration of clinical and radiographic findings allows for a comprehensive assessment of the VPT outcome. The following table summarizes the major assessment criteria:

Clinical and radiographic assessments are complementary approaches to evaluate the healing of the periodontal–pulpal interface after VPT using calcium-silicate bioceramics. Calcium-silicate materials promote dentin bridge formation and maintain PDL integrity, which can be observed radiographically, while clinical parameters such as pain absence and preserved pulp vitality confirm functional success. Regular monitoring ensures early detection of complications and informs the long-term prognosis of treated teeth (Singh, 2019; Bogen, 2016; Song et al., 2020, 2021).

Challenges and Limitations

Vital pulp therapy (VPT) using calcium-silicate bioceramics has shown promising outcomes in promoting reparative dentin formation and preserving pulp vitality. However, several challenges and limitations affect the predictability and long-term success of periodontal–pulpal interface healing.

Technical Challenges

The success of VPT heavily depends on clinical technique. Precise removal of inflamed tissue, adequate hemostasis, and proper placement of bioceramic materials are critical. Incomplete removal of infected pulp tissue may compromise healing, resulting in persistent inflammation or necrosis (Singh, 2019; Ashraf et al., 2017). Additionally, the handling properties of some calcium-silicate bioceramics, such as extended setting time and viscosity, can make clinical manipulation difficult (Bogen, 2016).

Biological Limitations

Despite favorable bioactivity, the healing potential of the pulp is influenced by the extent of injury, patient age, and systemic health. Older patients or teeth with extensive pulp inflammation may exhibit reduced regenerative capacity, limiting interface healing (Song et al., 2020; Xavier et al., 2021). Moreover, although bioceramics stimulate mineralized tissue formation, incomplete sealing at the interface may allow microleakage, leading to bacterial contamination and impaired periodontal–pulpal regeneration (Song et al., 2021).

Material-Related Limitations

While calcium-silicate bioceramics are biocompatible and bioactive, some material limitations exist:

- **Setting time**: Prolonged setting may affect immediate restoration procedures.
- **Solubility and dimensional stability**: Certain formulations may exhibit slight solubility in oral fluids, affecting long-term sealing (Bogen, 2016).
- **Cost**: Bioceramics are relatively expensive compared to traditional materials, which can limit accessibility in routine practice.

Evidence Gaps

Current research includes in vitro and case-based studies, but long-term randomized clinical trials are limited. Evidence regarding the comparative efficacy of different bioceramic formulations in interface healing remains insufficient (Singh, 2019; Xavier et al., 2021). Additionally, variations in evaluation methods—radiographic, histological, and clinical—challenge standardization of outcome measures.

Overall, while calcium-silicate bioceramics offer substantial benefits for VPT, overcoming these technical, biological, and material-related challenges is essential to optimize periodontal–pulpal interface healing.

CONCLUSION

Periodontal–pulpal interface healing following vital pulp therapy using calcium-silicate bioceramics demonstrates promising outcomes both clinically and biologically. Calcium-silicate bioceramics have shown favorable biocompatibility, bioactivity, and the ability to promote reparative dentin formation, supporting effective communication and healing between the pulp and periodontal tissues (Singh, 2019; Song, Li, Tang, Chen, & Yuan, 2021). Clinical reports have indicated that these materials provide reliable sealing, reduced inflammatory responses, and long-term stability, enhancing the success of vital pulp therapy procedures (Ashraf, Rahmati, & Amini, 2017; Bogen, 2016).

Experimental and clinical evidence further confirms that calcium-silicate bioceramics support both in vitro and in vivo regeneration of pulp and adjacent periodontal structures, demonstrating their potential to improve treatment predictability and preserve tooth vitality (Song, Sun, Chen, & Yuan, 2020; Xavier, Costa, Caramelo, Palma, & Ramos, 2021). Despite these advantages, factors such as patient condition, tooth characteristics, and proper material handling remain critical to achieving optimal healing outcomes.

Overall, the integration of calcium-silicate bioceramics in vital pulp therapy represents a significant advancement in endodontics, facilitating predictable periodontal–pulpal interface healing while maintaining tooth vitality. Continued research into their biological mechanisms and long-term clinical performance will further enhance their application in modern restorative and regenerative dentistry.

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