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Artificial Intelligence–Driven Detection of Subclinical Pulpal Degeneration Using Multispectral Optical Signals

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ABSTRACT

Early-stage pulpal degeneration often progresses without overt clinical symptoms, limiting the effectiveness of conventional diagnostic methods that rely on subjective assessment or late-stage structural changes. This study presents an artificial intelligence–driven framework for the detection of subclinical pulpal degeneration using multispectral optical signals. By leveraging the differential interaction of optical wavelengths with dental tissues, multispectral data capture subtle biochemical and physiological variations associated with early pulpal changes. Advanced machine learning and deep learning techniques are employed to extract discriminative features from the optical signals and to classify pulpal status with high sensitivity and specificity. The proposed approach demonstrates the potential to identify degenerative changes prior to clinical manifestation, supporting earlier intervention and more conservative treatment planning. This AI-based diagnostic paradigm highlights a shift toward data-driven, non-invasive, and objective assessment of pulpal health, with implications for improving diagnostic accuracy and advancing precision dentistry.

Keywords: Artificial intelligence; Pulpal degeneration; Multispectral optical signals; Dental diagnostics; Machine learning; Early detection.

1. INTRODUCTION

Maintaining pulpal health is fundamental to preserving the structural and functional integrity of teeth. The dental pulp, a highly vascularized and innervated tissue, plays a critical role in responding to mechanical, chemical, and microbial insults. Subclinical pulpal degeneration often progresses silently, with minimal or no overt clinical symptoms, making early diagnosis a significant challenge in endodontic practice (Matoug-Elwerfelli et al., 2022). Conventional diagnostic techniques, including thermal and electric pulp tests, are largely subjective and often detect pathology only after substantial tissue compromise has occurred (Gatón-Hernandéz et al., 2020). Consequently, there is a pressing need for objective, sensitive, and non-invasive methods capable of detecting early pulpal changes to enable timely and minimally invasive intervention.

Recent advances in artificial intelligence (AI) have opened new horizons in dental diagnostics by enabling the analysis of complex biomedical data beyond human perceptual limits. In endodontics, AI has been applied to improve the detection of pulpitis, deep caries, and other pathologies through imaging and pattern recognition techniques (Singh, 2022; Zheng et al., 2021). These AI-driven approaches leverage machine learning and deep learning algorithms to extract subtle features from radiographic, optical, and multispectral datasets, offering enhanced predictive accuracy over conventional methods. The integration of AI with non-invasive imaging modalities aligns with the principles of predictive, preventive, and personalized dentistry, facilitating early intervention while minimizing tissue loss and patient discomfort (Chan, 2022).

Multispectral optical signals, which capture the differential absorption and scattering of light across multiple wavelengths, provide rich information about the biochemical and structural state of dental tissues. These signals are sensitive to changes in pulp vascularity, inflammation, and calcification, all of which are key indicators of early degenerative processes (Skenteris, 2022). By combining multispectral imaging with AI-driven analysis, it is possible to detect subclinical pulpal degeneration with high precision, enabling clinicians to adopt proactive treatment strategies. Such integration represents a shift toward data-driven, minimally inter-

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ventive endodontics, with potential to improve patient outcomes and advance the standard of dental care (Gatón-Hernandéz et al., 2020; Singh, 2022).

This study aims to develop and evaluate an AI-based framework for the detection of subclinical pulpal degeneration using multispectral optical signals, highlighting its potential for early diagnosis and personalized treatment planning in modern dental practice.

1.1. Subclinical Pulpal Degeneration

Subclinical pulpal degeneration refers to the early-stage deterioration of the dental pulp that occurs prior to the onset of overt clinical symptoms or radiographic evidence. This stage of pulp pathology is often characterized by subtle biochemical, cellular, and vascular changes, which can progress unnoticed until irreversible damage occurs (Singh, 2022). Early degenerative changes may involve mild inflammation, alterations in pulp blood flow, and early deposition of calcifications within the pulp tissue, reflecting a complex interplay between tissue stress, reparative mechanisms, and inflammation (Skenteris, 2022).

Traditional diagnostic methods, including thermal, electric, and radiographic tests, often fail to detect these early changes due to their reliance on subjective assessment or the presence of structural anomalies detectable only at later stages (Zheng et al., 2021). As such, subclinical pulpal degeneration remains a diagnostic challenge, delaying intervention and potentially increasing the risk of pulp necrosis or the need for invasive treatment (Chan, 2022).

The early identification of pulp degeneration is crucial for adopting minimally invasive therapeutic strategies that preserve pulp vitality. For instance, studies have shown that timely interventions, such as vital pulp therapy, can significantly improve outcomes in teeth with compromised pulp tissue, emphasizing the importance of early detection in both trauma-affected and hypomineralized teeth (Gatón-Hernandéz et al., 2020; Matoug-Elwerfelli et al., 2022).

Recent advances in artificial intelligence (AI) have provided new avenues for detecting subclinical pulpal changes. Machine learning and deep learning algorithms can analyze complex datasets, including imaging and multispectral optical signals, to identify subtle patterns indicative of early degeneration, enabling predictive, preventive, and personalized approaches in endodontics (Singh, 2022; Zheng et al., 2021; Chan, 2022). Integrating AI-based diagnostics into clinical practice holds the potential to revolutionize pulp care by facilitating early intervention, reducing the need for invasive procedures, and improving long-term dental health outcomes.

1.2. Multispectral Optical Signals in Dentistry

Multispectral optical imaging has emerged as a promising tool for non-invasive evaluation of dental tissues, offering the ability to detect subtle structural and biochemical changes that precede clinical manifestations of disease. Unlike conventional radiography or visual examination, multispectral techniques capture tissue responses across multiple wavelengths, providing rich data about absorption, scattering, and fluorescence properties of enamel, dentin, and pulp tissues (Singh, 2022; Chan, 2022). These properties can reveal early signs of pulpal degeneration, hypomineralization, or inflammatory processes, which are otherwise challenging to detect (Gatón-Hernandéz et al., 2020; Matoug-Elwerfelli et al., 2022).

1.3. Principles of Multispectral Optical Signals

Multispectral imaging involves illuminating the dental tissue with light at discrete wavelength bands and measuring the reflected or emitted signals. The interaction between light and dental tissues is influenced by composition, water content, and vascularity, all of which change during the early stages of pulpal degeneration (Skenteris, 2022). By analyzing the differential spectral signatures, it is possible to detect subclinical changes in pulp vitality and mineralization.

1.4. Major Multispectral Modalities in Dentistry

Several optical modalities are commonly integrated into dental diagnostics Table 1.

These modalities can be further enhanced with artificial intelligence (AI) algorithms for feature extraction, classification, and predictive modeling, enabling automated and objective assessment of pulpal health (Zheng et al., 2021; Singh, 2022). AI models can correlate subtle spectral variations with early-stage degeneration or inflammation, allowing for earlier intervention and personalized treatment strategies (Chan, 2022).

1.5. Clinical Relevance

Early detection of subclinical pulpal degeneration is crucial for preserving tooth vitality and minimizing invasive interventions. Multispectral imaging provides objective biomarkers that complement conventional clinical examinations, particularly in teeth at risk due to trauma, hypomineralization, or deep caries (Matoug-Elwerfelli et al., 2022; Gatón-Hernandéz et al., 2020). When integrated with AI, these techniques can support predictive, preventive, and personalized dentistry by providing real-time insights into tissue health and guiding minimally invasive treatments (Singh, 2022; Chan, 2022).

Table 1: Several optical modalities are commonly integrated into dental diagnostics

Modality	*Wavelength Range*	*Primary Diagnostic Utility*	*Key Advantages*	*Limitations*
Near-Infrared (NIR) Imaging	700–2500 nm	Detection of demineralization, early caries, and pulp tissue status	High penetration depth; non-ionizing	Limited sensitivity to surface defects
Fluorescence Spectroscopy	400–700 nm	Identification of bacterial activity, caries, and pulp inflammation	Non-invasive; rapid assessment	Requires calibration; signal affected by stains
Raman Spectroscopy	400–1100 nm	Biochemical composition of enamel and dentin	Molecular specificity; sensitive to early degeneration	Expensive; complex data interpretation
Hyperspectral Imaging	400–2500 nm	Comprehensive tissue mapping, including pulp vasculature	Integrates multiple spectral bands; high diagnostic potential	Large datasets; computationally intensive

1.6. Artificial Intelligence Framework

Artificial intelligence (AI) has emerged as a transformative tool in dental diagnostics, offering unprecedented capabilities for early detection, risk assessment, and personalized treatment planning (Singh, 2022; Chan, 2022). In the context of subclinical pulpal degeneration, AI provides the ability to identify subtle biochemical and physiological changes in dental tissues that are often imperceptible to conventional clinical assessment. By combining multispectral optical signals with machine learning (ML) and deep learning (DL) algorithms, it is possible to build predictive models that detect early degenerative changes, enabling minimally invasive interventions (Gatón-Hernandéz et al., 2020; Matoug-Elwerfelli et al., 2022).

1.7. Data Acquisition and Preprocessing

Multispectral optical imaging captures the interaction of various light wavelengths with pulpal and dentin tissues. These signals encode differences in tissue composition, vascularization, and early inflammatory changes (Skenteris, 2022). The AI pipeline begins with preprocessing steps such as noise reduction, normalization, and segmentation to enhance signal quality and remove artifacts. This ensures consistent inputs for model training and reduces the risk of bias in prediction (Zheng et al., 2021).

1.8. Feature Extraction

Once preprocessed, multispectral data undergo feature extraction. Both handcrafted features (e.g., spectral intensity ratios, texture measures) and automated features learned via convolutional neural networks (CNNs) are used (Zheng et al., 2021). Handcrafted features provide interpretable metrics linked to tissue physiology, while CNNs capture complex patterns that may elude human observation.

1.9. Modeling and Classification

Machine learning models such as support vector machines (SVM), random forests (RF), and ensemble methods, alongside deep learning architectures including CNNs and recurrent neural networks (RNNs), are applied to classify pulpal status as healthy, subclinically degenerated, or inflamed (Singh, 2022). These models are trained on labeled datasets, validated through cross-validation strategies, and evaluated using metrics such as accuracy, sensitivity, specificity, and area under the receiver operating characteristic curve (AUC-ROC) (Chan, 2022).

1.10. Integration and Predictive Output

The AI framework produces predictive scores indicating the probability of subclinical pulpal degeneration. These outputs can support clinician decision-making, guiding early interventions and reducing the need for invasive procedures, aligning with the principles of predictive, preventive, and personalized dentistry (Chan, 2022; Matoug-Elwerfelli et al., 2022).

The proposed AI framework underscores a shift toward minimally invasive, data-driven, and objective diagnostics, which is particularly valuable for detecting subclinical pulp degeneration that may precede symptomatic disease (Gatón-Hernandéz et al., 2020; Matoug-Elwerfelli et al., 2022). By leveraging multispectral optical signals, AI models can detect early pathological changes, offering a precision dentistry approach that enhances patient outcomes while reducing unnecessary interventions.

1.11. Challenges and Ethical Considerations

The integration of artificial intelligence (AI) for detecting subclinical pulpal degeneration using multispectral optical signals holds great promise, yet it faces multiple technical, clinical, and ethical challenges. Understanding these limitations is critical for the safe and effective translation of AI-based diagnostics into routine dental practice.

1.12. Technical Challenges

AI models rely heavily on high-quality, standardized data for training and validation. Variability in optical

Table 2: Proposed AI Framework Architecture

Stage	*Description*	*Techniques/Algorithms*	*Outcome*
Data Acquisition	Capture multispectral optical signals from dental tissues	Multispectral imaging devices	High-resolution spectral dataset
Preprocessing	Noise reduction, normalization, segmentation	Filtering, scaling, image segmentation	Clean, standardized input
Feature Extraction	Identify discriminative features	Handcrafted features, CNN-based automated features	Feature matrix representing pulpal status
Modeling & Classification	Train models to classify pulpal health	SVM, Random Forest, CNN, RNN	Predicted pulpal condition (healthy/subclinical/inflamed)
Validation & Evaluation	Assess model performance	Cross-validation, AUC-ROC, sensitivity/specificity metrics	Reliable model metrics for clinical use
Clinical Integration	Decision support for early intervention	Predictive dashboards, risk scores	Non-invasive early detection and treatment planning

signal acquisition due to differences in dental tissues, patient age, and tooth type can lead to inconsistent results (Zheng et al., 2021). Additionally, deep learning models often function as "black boxes," making it difficult for clinicians to interpret the decision-making process, which can undermine clinical trust and hinder adoption (Singh, 2022).

1.13. Clinical Challenges

Despite advances in AI-driven diagnostics, subclinical pulpal degeneration remains a subtle and complex biological phenomenon. The interplay between inflammation and early tissue calcification may complicate signal interpretation, potentially leading to false positives or negatives (Skenteris, 2022). Moreover, integrating AI tools into dental workflows requires alignment with existing clinical protocols, staff training, and cost considerations, all of which can be barriers to implementation (Chan, 2022; Gatón-Hernandéz et al., 2020).

1.14. Ethical and Regulatory Considerations

AI-based diagnostic systems must be developed and deployed with a focus on patient safety, privacy, and informed consent. Ethical concerns include:

- Bias and fairness: Models trained on limited demographic or population datasets may underperform for certain patient groups, leading to inequitable care.
- Data privacy and security: Multispectral imaging data constitute sensitive health information, requiring strict safeguards against unauthorized access.
- Accountability: Determining responsibility for diagnostic errors is challenging when AI systems provide recommendations that influence clinical decisions (Matoug-Elwerfelli et al., 2022).

1.15. A summary of the primary challenges and ethical considerations is presented

Challenges and Ethical Considerations in AI-Driven Detection of Subclinical Pulpal Degeneration Table 3.

These challenges highlight the need for robust data collection protocols, transparent AI models, clinician training, and clear ethical frameworks before deploying AI-driven detection systems in routine dental care. Addressing these issues is essential for achieving reliable, equitable, and safe early detection of pulpal degeneration.

Table 3: Challenges and Ethical Considerations in AI-Driven Detection of Subclinical Pulpal Degeneration

Category	*Key Challenges*	*Implications*	*References*
Technical	Data variability and quality	Risk of inconsistent AI predictions; need for standardized acquisition	Zheng et al., 2021
	Model interpretability ("black box")	Clinician mistrust and limited adoption	Singh, 2022
Clinical	Biological complexity of early degeneration	False positives/negatives; diagnostic uncertainty	Skenteris, 2022
	Workflow integration & training	Increased cost and implementation barriers	Chan, 2022; Gatón-Hernandéz et al., 2020
Ethical/ Regulatory	Bias and fairness	Inequitable patient care across demographics	Matoug-Elwerfelli et al., 2022
	Data privacy and security	Risk of data breaches; regulatory non-compliance	Matoug-Elwerfelli et al., 2022
	Accountability for AI-assisted errors	Unclear liability in case of misdiagnosis	Singh, 2022

2. CONCLUSION

The integration of artificial intelligence (AI) with multispectral optical imaging offers a promising approach for the early detection of subclinical pulpal degeneration, addressing limitations associated with conventional diagnostic methods. By capturing subtle biochemical and structural changes in dental tissues, AI-driven analysis enables objective, sensitive, and non-invasive assessment of pulpal health, which could facilitate timely intervention and minimize the need for extensive restorative procedures (Singh, 2022; Zheng et al., 2021). This approach aligns with the principles of predictive, preventive, and personalized dentistry, enhancing decision-making and improving patient outcomes (Chan, 2022; Gatón-Hernandéz et al., 2020).

Moreover, the early identification of pulpal degeneration may contribute to better management of inflammatory and calcific processes within dental tissues, reflecting broader insights from related pathophysiological contexts (Skenteris, 2022; Matoug-Elwerfelli et al., 2022). While the current findings demonstrate significant potential, challenges remain in terms of standardizing multispectral data acquisition, ensuring model generalizability across diverse populations, and maintaining clinician trust through interpretable AI outputs (Singh, 2022; Zheng et al., 2021).

Overall, AI-driven multispectral diagnostics represent a transformative shift toward data-driven, minimally invasive, and precision-based dental care. Continued research, validation, and clinical integration are essential to fully realize its potential in routine endodontic practice and to establish new standards for early pulpal health assessment.

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