

Multispectral Imaging for Differentiating Inflamed but Viable Pulp From Necrotic Pulp

Shelly Singh

DDS (University of Colorado), BDS, MDS (Endodontics)

ABSTRACT

Pulp sensibility testing is a method used to evaluate the response of the pulpal nerve, not to directly assess the blood supply and viability of the pulpal tissues, and therefore is not a good method to distinguish between inflamed but viable dental pulp and necrotic pulp. Multispectral imaging may be a non-invasive way in which tissue responses at various wavelengths can be used to detect optical patterns for pulpal oxygenation, perfusion, and structural changes. This article will review the pathogenesis of pulpal inflammation and necrosis and discuss the possible use of multispectral imaging in improving the diagnostic differentiation. It also takes into account the application of AI and ML for spectral data processing and feature extraction and to help classify pulp conditions. A special focus is on diagnostic accuracy, sensitivity, specificity, reproducibility and clinical feasibility. The imaging performance, however, may be compromised by problems of penetration, tooth structure, restorations, heterogeneous inflammation and partial pulp necrosis. Thus, multispectral imaging must be assessed together with the standard clinical evaluations and the use of suitable reference standards. Additional experimental and prospective clinical studies are needed to define standard imaging protocols, to validate imaging diagnostic thresholds, and to determine its utility in treatment planning. In the long term, this can contribute to better pulp diagnosis and maintain vitality in the pulp tissue by biologically-driven endodontics.

Keywords: Multispectral imaging, dental pulp vitality, pulp inflammation, pulp necrosis, endodontic diagnosis, artificial intelligence, machine learning, pulp tissue preservation.

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INTRODUCTION

A proper diagnosis and treatment planning of dental pulp status is crucial for endodontic treatment. The dental pulp is a specialized connective tissue, which is vascularized, innervated, immunized, and composed of odontoblasts involved in nutrition, sensory, defense, and reparative activities. After bacterial invasion, trauma, or operative injury the pulp may start to respond to the insult with varying degrees and distribution of inflammation. Importantly, the presence of inflammation does not necessarily mean that the pulp is totally dead; some portions may be biologically active and be able to heal despite clinical signs of irreversible pulpitis (Yu & Abbott, 2007; Goldberg et al., 2015). This leaves the definite diagnosis of inflamed but still vital pulp from necrotic pulp as perhaps the most difficult diagnosis in modern endodontics.

Traditional pulp evaluation is based on clinical signs, physical examination, and radiographic examination, as well as sensibility tests, such as thermal and electrical stimulation. These techniques offer valuable diagnostic data, but have some

drawbacks since they do not measure pulpal blood flow or cell viability directly. There can be false-positive or false-negative results, especially in teeth that have large restorations, young apices, trauma, or complex inflammatory diseases. In addition, inflammation of the pulp can be limited and viable and necrotic tissue can exist in the same pulp chamber or root canal system. The complexities emphasize the need for a combination of clinical and biological indicators when evaluating pulp status, and not just a single indicator (Sigurdsson, 2003; Abbott & Yu, 2007; Torabinejad & Shabahang, 2009).

It is especially important to differentiate between inflammation and necrosis because the choice of therapy depends on that. Irreversible pulpitis is a diagnosis that suggests that the pulp may be alive but unreceptive to the care provided by carefully selected vital pulp therapy procedures. These interventions are successful when they are related to the level of inflammation, the condition of the remaining pulp, microbial control, and proper environment for healing (Lin et al., 2020; Kahler et al., 2023). Research on reparative processes

has also demonstrated the importance of understanding the interactions between inflammatory mediators, immune responses, tissue damage, and cellular repair mechanisms (El Karim et al., 2021). Similarly, the relationship between inflammation and regeneration suggests that the presence of inflammation alone should not automatically be interpreted as evidence of complete pulp destruction (Goldberg et al., 2015). More precise diagnostic methods are therefore needed to support tissue-preserving treatment decisions.

Recent investigations into nontraditional pulp vitality assessment methods have explored approaches that may provide information beyond conventional sensibility testing. These developments include techniques designed to evaluate blood flow, oxygenation, and other physiological characteristics of pulpal tissue. Afkhami et al. (2024) highlighted the growing interest in alternative approaches to pulp vitality assessment, reflecting the need for more objective and biologically relevant diagnostic methods. Meanwhile, systematic evidence indicates that diagnosing pulp inflammation remains challenging because clinical symptoms and conventional examination findings do not always correspond directly with the underlying inflammatory condition (Zanini et al., 2017). Emerging diagnostic strategies, including the investigation of molecular biomarkers of inflammation and cell death, may offer additional opportunities to characterize pulp status more accurately (Lennon, 2024; Bhat et al., 2024).

Multispectral imaging represents a potential complementary approach for addressing this diagnostic challenge. The technique involves acquiring and analyzing images at multiple wavelengths to identify differences in the optical properties of tissues. Depending on the selected wavelengths and imaging configuration, spectral measurements may provide information related to tissue composition, oxygenation, vascular characteristics, and structural changes. By examining patterns across several spectral bands, multispectral imaging could potentially help distinguish inflamed but viable pulp from necrotic tissue. However, its effectiveness for dental pulp assessment remains a research question requiring direct experimental and clinical validation. Findings from other applications of spectral imaging, including the use of hyperspectral imaging and machine learning to detect early plant disease, demonstrate the broader potential of combining wavelength-specific information with computational classification, although these results cannot be directly generalized to human dental tissues (Velásquez et al., 2024). In addition, research into photobiomodulation and pulp-regenerative endodontics illustrates the continuing interest in technologies that support the biological assessment and preservation of pulpal tissues (Yong et al., 2023).

Integrating multispectral imaging with artificial intelligence may further improve its potential diagnostic value. Machine-learning algorithms could analyze spectral patterns, identify relevant features, and estimate the likelihood of viable inflammation or pulp necrosis when trained and

validated using appropriate reference standards. Such systems would need to account for variations in enamel and dentine thickness, tooth type, restorations, blood supply, inflammation severity, and partial necrosis. Diagnostic performance should be established through studies evaluating sensitivity, specificity, reproducibility, and agreement with reliable clinical and biological assessments. Importantly, multispectral imaging should initially be considered an investigational or complementary technique rather than an established replacement for conventional diagnostic procedures.

This article examines the potential of multispectral imaging for differentiating inflamed but viable dental pulp from necrotic pulp. It discusses the biological characteristics underlying these conditions, the optical principles relevant to pulp assessment, and the possible integration of multispectral data with artificial intelligence. It also considers the methodological challenges, clinical validation requirements, and future research directions necessary to establish whether this technology can improve diagnostic accuracy and support evidence-based, biologically oriented endodontic treatment.

Biological Basis of Pulp Inflammation and Necrosis

Dental pulp is a specialized connective tissue containing blood vessels, nerves, odontoblasts, fibroblasts, immune cells, and extracellular matrix components that collectively maintain tooth vitality, respond to injury, and support tissue repair. When exposed to bacterial invasion, dental caries, trauma, or restorative procedures, the pulp initiates an inflammatory response intended to eliminate harmful stimuli and promote healing. However, because the pulp is enclosed within rigid dentinal walls, inflammation may increase tissue pressure, compromise microcirculation, and contribute to cellular injury. The biological outcome depends on the intensity and duration of the insult, the distribution of inflammation, the remaining vascular supply, and the pulp's reparative capacity (Yu & Abbott, 2007; Torabinejad & Shabahang, 2009). Understanding these processes is essential for developing diagnostic approaches capable of distinguishing inflamed but viable pulp from necrotic tissue.

Pulp inflammation involves interactions between microbial products, resident immune cells, inflammatory mediators, and the pulpal microvasculature. Early inflammatory responses may produce vasodilation, increased vascular permeability, immune-cell recruitment, and changes in local blood flow. These processes can occur while viable odontoblasts, fibroblasts, endothelial cells, and other pulp cells remain functional. Depending on the severity of the injury and the effectiveness of treatment, the tissue may recover, undergo localized damage, or progress toward more extensive degeneration. Consequently, the presence of inflammation does not automatically indicate complete loss of pulp vitality. Goldberg et al. (2015) examined the relationship between inflammation and pulp healing, while El Karim et al. (2021) discussed the cellular and molecular processes involved

in reparative responses within inflamed pulp tissue. These biological considerations support the need to distinguish inflammatory activity from irreversible tissue destruction.

The distinction between inflamed viable pulp and necrotic pulp is particularly important in clinical endodontics. Viable pulp may exhibit reversible or persistent inflammation, altered vascular responses, and varying degrees of cellular injury while retaining sufficient living tissue to support repair. In contrast, pulp necrosis involves the death of pulp cells and the loss of normal tissue function, potentially affecting the entire pulp or only particular regions. Therefore, a tooth may contain both viable inflamed tissue and localized necrotic areas, making diagnosis more complex than a simple binary classification. Kahler et al. (2023) and Lin et al. (2020) highlighted the biological basis for considering vital pulp therapy in selected permanent teeth diagnosed with irreversible pulpitis. Their work reinforces the principle that clinical symptoms alone may not fully represent the histological condition or healing potential of the pulp.

Conventional diagnostic methods, including cold testing, heat testing, and electric pulp testing, primarily assess neural responsiveness rather than directly establishing the presence of an intact blood supply. A positive response indicates sensory nerve activity but does not independently confirm the overall health of the pulp, while a negative response does not invariably establish necrosis. Sigurdsson (2003) and Abbott and Yu (2007) emphasized the importance of interpreting pulp findings within a broader diagnostic framework that incorporates symptoms, clinical examination, and the condition of the surrounding tissues. Zanini et al. (2017) further examined the challenges of diagnosing pulp inflammation through clinical findings and inflammatory mediators. More recently, Afkhami et al. (2024) reviewed nontraditional approaches to pulp vitality assessment, supporting continued investigation into methods that can provide information beyond sensory responses.

Multispectral imaging may offer a complementary approach by examining wavelength-dependent optical signals associated with tissue composition, blood content, and oxygenation. Because viable inflamed pulp may retain perfusion despite altered vascular function, whereas extensively necrotic pulp is expected to show substantially reduced or absent local perfusion, optical measurements could potentially help differentiate these conditions. Nevertheless, the diagnostic interpretation of spectral signals requires caution. Changes in inflammation do not necessarily produce a predictable optical signature, and the signals detected through enamel and dentin may be influenced by tooth structure, restorations, pigmentation, and the depth or distribution of the affected tissue. Thus, multispectral imaging should be regarded as a promising investigational method rather than an established standalone diagnostic test. Bhat et al. (2024) discussed the need for improved approaches to diagnosing irreversible pulpitis, while Lennon (2024) investigated molecular biomarkers associated with pulp inflammation and cell death, highlighting

the broader search for objective indicators of pulp status.

In summary, the biological distinction between inflamed viable pulp and necrotic pulp rests on the preservation or loss of cellular viability and tissue perfusion rather than on the presence of pain or inflammation alone. Multispectral imaging could potentially improve this distinction by providing optical information associated with blood supply and oxygenation. However, partial necrosis, heterogeneous inflammation, and the optical properties of surrounding dental tissues remain important challenges. Integrating multispectral measurements with established clinical tests and, where appropriate, biological reference assessments may provide a more reliable foundation for future diagnostic protocols.

Principles and Applications of Multispectral Imaging

Multispectral imaging is an optical imaging approach that captures information from a target tissue at multiple selected wavelengths, allowing differences in light absorption, reflection, and scattering to be analyzed. In endodontics, this technology has potential as a non-invasive method for assessing dental pulp vitality by identifying optical signals associated with tissue oxygenation, vascular perfusion, and changes in tissue composition. Unlike conventional pulp sensibility tests, which evaluate the neural response to thermal or electrical stimulation, optical approaches aim to obtain information related more directly to the physiological status of the pulp. Afkhami et al. (2024) highlighted the importance of developing nontraditional pulp vitality assessment methods to address the limitations of conventional diagnostic approaches. Nevertheless, multispectral imaging should be considered an emerging diagnostic possibility requiring further validation, rather than an established clinical method for differentiating inflamed viable pulp from necrotic pulp.

The underlying principle of multispectral imaging is that biological tissues interact differently with light at different wavelengths. When light is directed toward a tooth, some wavelengths may be absorbed by blood and its oxygenated or deoxygenated components, while other portions are reflected or scattered by dental and pulpal tissues. By capturing and comparing these wavelength-dependent signals, an imaging system may identify patterns associated with changes in pulpal blood content, oxygenation, and tissue optical properties. However, the dental pulp is located beneath enamel and dentine, which influence light transmission and scattering. Consequently, the interpretation of pulpal signals requires appropriate optical instrumentation, signal processing, and validation against reliable clinical reference standards.

The biological interpretation of these signals is particularly important because inflammation does not necessarily indicate complete loss of pulp vitality. An inflamed pulp may retain viable cells, residual blood supply, and reparative potential despite substantial inflammatory changes. Kahler et al. (2023) and Lin et al. (2020) discussed the biological basis of vital pulp therapy in permanent teeth diagnosed with irreversible

Table 1: Biological and Diagnostic Differences Between Inflamed Viable Pulp and Necrotic Pulp

<i>Biological or diagnostic feature</i>	<i>Inflamed but viable pulp</i>	<i>Necrotic pulp</i>
Cellular viability	Living pulp cells remain, although some may be injured or dysfunctional	Cell death is present in affected tissue
Blood supply	Perfusion is retained but may be altered or locally compromised	Perfusion is generally absent in fully necrotic regions
Oxygenation	May be reduced or heterogeneous because of inflammatory vascular changes	Often markedly reduced or absent in necrotic regions
Inflammatory response	May involve immune-cell recruitment and inflammatory mediator release	May coexist with inflammation, particularly at the interface with viable tissue
Tissue distribution	Inflammation may be localized or widespread, with variable reparative potential	Necrosis may be partial or complete
Neural responsiveness	Responses may be exaggerated, prolonged, reduced, or absent, depending on the condition	Responses are generally absent when pulp tissue is completely necrotic, although mixed tissue states complicate interpretation
Potential for healing	Depends on the extent of injury, remaining viable tissue, microbial control, and treatment	Necrotic tissue cannot recover its original cellular vitality
Potential multispectral indication	Detectable optical signals related to residual perfusion or blood oxygenation may be present	Reduced perfusion-related signals may occur in necrotic regions
Diagnostic limitation	Inflammation severity cannot be reliably inferred from a single optical measurement	Partial necrosis may produce signals resembling those of viable tissue
Clinical implication	Selected cases may be candidates for vital pulp therapy following appropriate assessment	Requires evaluation for endodontic treatment based on the overall diagnosis

Source: Synthesized from Yu and Abbott (2007), Sigurdsson (2003), Abbott and Yu (2007), Goldberg et al. (2015), Lin et al. (2020), El Karim et al. (2021), Kahler et al. (2023), Afkhami et al. (2024), and Bhat et al. (2024). The multispectral indications are proposed diagnostic applications and require clinical validation.

pulpitis, emphasizing the importance of evaluating the actual biological condition of the tissue rather than relying exclusively on diagnostic labels. Similarly, Yu and Abbott (2007) described the protective, sensory, and reparative functions of the dental pulp, while Goldberg et al. (2015) examined the relationship between inflammation, pulp healing, and regeneration. These findings provide a biological rationale for developing imaging methods capable of distinguishing inflammation in living tissue from extensive or complete tissue necrosis.

Optical Signals Associated With Pulp Vitality

The application of multispectral imaging to pulp assessment may involve several complementary optical indicators. Oxygenation-sensitive measurements could help characterize differences in the relative oxygenation of blood within the pulp, while perfusion-related measurements could provide evidence of circulating blood. Spectral reflectance patterns may also contribute information about tissue composition and optical changes associated with inflammation or necrosis. However, these indicators are not interchangeable. A detectable optical signal does not necessarily establish normal pulp function, and reduced signal intensity does not independently confirm necrosis. Inflammation can alter local blood flow, vascular permeability, and tissue pressure, producing physiological

changes that complicate interpretation (Torabinejad & Shabahang, 2009; El Karim et al., 2021).

The distinction between viable inflamed pulp and necrotic pulp may therefore depend on combining several spectral features rather than interpreting a single wavelength or measurement. In viable inflamed tissue, the imaging system may detect residual perfusion or oxygenation-related signals despite physiological abnormalities. In necrotic tissue, these signals may be markedly reduced or absent, although partial necrosis and mixed tissue states may produce intermediate patterns. These possibilities require experimental confirmation because optical measurements may also be affected by tooth anatomy, restorations, the depth of the pulp chamber, and the technical characteristics of the imaging device.

Image Processing and Machine-Learning Applications

Multispectral imaging may be strengthened through computational analysis of spectral data. The processing workflow can include image acquisition, calibration, noise reduction, segmentation of the tooth region, extraction of wavelength-specific features, and classification of the resulting patterns. Machine-learning models could then be trained to identify combinations of features associated with clinically characterized pulp conditions. Such a framework may support

the differentiation of healthy pulp, inflamed but viable pulp, and necrotic pulp, provided that the training data adequately represent the variability encountered in clinical practice.

The potential value of machine learning is illustrated by Velásquez et al. (2024), who investigated hyperspectral imaging combined with machine learning for early detection of anthracnose in mangoes. Although this study concerns agricultural disease detection rather than dental pulp diagnosis, it demonstrates how wavelength-dependent imaging data can be combined with computational methods to recognize patterns that may not be readily distinguished through conventional visual inspection. Its relevance to endodontics is methodological; its findings cannot be interpreted as direct evidence of diagnostic accuracy for dental pulp conditions.

For clinical implementation, an artificial intelligence model would require well-characterized datasets obtained from different tooth types, patient populations, and disease stages. Model performance should be assessed using sensitivity, specificity, predictive values, calibration, and external validation. The classification system should also indicate uncertainty where spectral patterns are ambiguous, particularly in cases of partial necrosis or severe inflammation. These requirements are consistent with the broader need for more reliable diagnostic strategies identified by Afkhami et al. (2024), Zanini et al. (2017), and Bhat et al. (2024).

Potential Clinical Applications

Multispectral imaging could eventually complement conventional clinical examinations by providing additional physiological information before treatment decisions are made.

For example, a tooth that produces an abnormal response to cold testing may still contain viable inflamed tissue that could be considered for vital pulp therapy. Conversely, an absence of sensibility response may warrant further investigation rather than automatically establishing complete necrosis. Sigurdsson (2003) and Abbott and Yu (2007) emphasized the importance of interpreting pulp diagnostic findings within a broader clinical assessment.

The potential applications extend to monitoring changes in pulp status over time, evaluating responses to conservative pulp treatment, and identifying cases that require further investigation. Serial imaging may help determine whether physiological signals remain stable, improve, or deteriorate following treatment. Research into molecular biomarkers of pulp inflammation and cell death may also provide complementary evidence for interpreting imaging results (Lennon, 2024). However, multispectral imaging should not replace established diagnostic procedures until its clinical reliability and added value have been demonstrated. Photobiomodulation and regenerative endodontic research further illustrate the importance of understanding tissue responses and healing processes when developing approaches intended to preserve or restore pulp function (Yong et al., 2023).

In summary, multispectral imaging offers a promising research direction for improving pulp vitality assessment by combining wavelength-dependent optical measurements with biological interpretation and computational analysis. Its principal potential lies in identifying evidence of residual perfusion and other physiological characteristics that may

Table 2: Principles, Potential Applications, and Diagnostic Limitations of Multispectral Imaging for Pulp Assessment

<i>Imaging principle or component</i>	<i>Potential application in pulp diagnosis</i>	<i>Main limitation or consideration</i>
Wavelength-dependent light absorption	Identifying spectral differences potentially associated with blood oxygenation and tissue composition	Signals may be influenced by enamel, dentine, and optical interference
Perfusion-sensitive measurements	Detecting evidence of residual pulpal blood flow in viable tissue	Reduced perfusion does not necessarily indicate complete necrosis
Oxygenation-sensitive measurements	Characterizing potential differences in oxygenation between pulp conditions	Oxygenation alone cannot reliably distinguish inflammation from necrosis
Spectral reflectance analysis	Identifying patterns associated with tissue physiological or structural changes	Requires standardized acquisition and calibration procedures
Image preprocessing and feature extraction	Improving signal consistency and identifying diagnostically relevant patterns	Noise, restorations, tooth anatomy, and device variation may affect results
Machine-learning classification	Combining spectral features to estimate whether pulp is viable, inflamed, or necrotic	Requires representative datasets, independent validation, and transparent performance reporting
Longitudinal imaging	Monitoring physiological changes after vital pulp therapy	Clinical thresholds and the relationship between signal changes and healing remain to be established

Source: Conceptual synthesis based on Afkhami et al. (2024), Sigurdsson (2003), Abbott and Yu (2007), Lin et al. (2020), El Karim et al. (2021), Bhat et al. (2024), and Velásquez et al. (2024). The proposed applications require validation and should not be interpreted as established clinical performance.

help distinguish inflamed but viable pulp from necrotic tissue. However, inflammation, partial necrosis, optical interference, and variations in tooth anatomy make this distinction challenging. Future research should prioritize clinically validated imaging protocols, representative datasets, and direct comparisons with established diagnostic assessments to determine whether multispectral imaging can provide meaningful improvements in endodontic decision-making.

Diagnostic Workflow and Clinical Validation

The clinical application of multispectral imaging for differentiating inflamed but viable dental pulp from necrotic pulp requires a structured diagnostic workflow integrating image acquisition, spectral analysis, clinical examination, and validation against appropriate reference standards. Conventional pulp sensibility tests, including thermal and electric pulp testing, remain important in clinical practice; however, they primarily evaluate neural responsiveness rather than directly establishing pulpal blood flow or tissue viability. Consequently, combining conventional tests with emerging vitality-assessment technologies may improve diagnostic interpretation and reduce the risk of inappropriate treatment decisions (Sigurdsson, 2003; Afkhami et al., 2024). A comprehensive diagnosis should also consider the patient's symptoms, clinical history, radiographic findings, and the condition of the surrounding periapical tissues (Abbott & Yu, 2007; Torabinejad & Shabahang, 2009).

Image Acquisition and Spectral Data Processing

The proposed diagnostic workflow begins with the acquisition of multispectral images at selected wavelengths capable of capturing differences in the optical properties of dental tissues. Depending on the imaging system, spectral measurements may provide information associated with tissue oxygenation, blood volume, perfusion, and structural characteristics. Nevertheless, these signals should be interpreted cautiously because enamel and dentine attenuate and scatter light, while restorations, calcification, and variations in tooth anatomy may influence signal quality. Therefore, wavelength selection and image acquisition protocols must be standardized to ensure consistent measurements across patients and tooth types.

Following image acquisition, preprocessing procedures should address background interference, illumination variability, sensor noise, and differences in image intensity. Regions of interest corresponding to the target tooth should then be identified, and relevant spectral features extracted for further analysis. Machine-learning algorithms may subsequently identify patterns associated with viable, inflamed, and necrotic pulp. The application of hyperspectral imaging and machine learning in other biological detection contexts demonstrates the potential of combining spectral information with computational classification, although its successful application to dental pulp diagnosis requires independent validation (Velásquez et al., 2024). In addition,

the broader review of nontraditional pulp vitality assessment by Afkhami et al. (2024) provides a relevant foundation for evaluating emerging diagnostic technologies.

Integration with Clinical Examination and Pulp Classification

Multispectral imaging should complement rather than replace established clinical diagnostic procedures. Initial assessment should document the patient's pain characteristics, relevant dental history, caries depth, previous restorations, percussion responses, and periapical findings. Thermal and electric pulp tests may provide additional information, but their results must be interpreted alongside the clinical presentation because a positive response does not necessarily establish healthy pulp, while a negative response does not independently confirm necrosis (Sigurdsson, 2003; Bhat et al., 2024).

The interpretation of multispectral findings must also recognize that pulp inflammation and necrosis are not always mutually exclusive conditions at the whole-tooth level. A tooth may contain inflamed but viable tissue in one region and necrotic tissue in another. Biological studies indicate that the inflamed pulp can retain reparative capacity, depending on the extent of tissue damage, the distribution of inflammation, and the remaining viable tissue (Goldberg et al., 2015; Lin et al., 2020; El Karim et al., 2021). Accordingly, imaging classifications should distinguish between evidence of viable inflamed tissue, findings suggestive of extensive necrosis, and indeterminate or mixed tissue states. This approach would support more biologically informed decisions regarding vital pulp therapy and other endodontic interventions (Kahler et al., 2023).

Diagnostic Validation and Performance Evaluation

Clinical validation is essential before multispectral imaging can be recommended for routine endodontic diagnosis. Studies should compare imaging classifications with a predefined reference standard that is appropriate to the clinical setting and ethically acceptable. Histological assessment may provide detailed information about inflammation and tissue necrosis when tissue is available from clinically indicated procedures, whereas intraoperative findings and longitudinal clinical outcomes may provide complementary evidence. No single reference method should be assumed to establish the full biological status of every pulp.

Diagnostic performance should be assessed using sensitivity, specificity, predictive values, receiver operating characteristic analysis, and agreement between evaluators. Reproducibility should also be examined across repeated measurements, different operators, and different clinical environments. These considerations are particularly important because pulp diagnosis remains challenging when clinical symptoms, neural responses, inflammatory mediators, and tissue-level pathology do not correspond directly (Zanini et al., 2017). Molecular biomarkers of inflammation and cell

death may provide additional evidence for future multimodal diagnostic approaches, although their clinical utility and standardization require further investigation (Lennon, 2024).

Challenges and Future Validation Priorities

Several challenges may influence the accuracy of multispectral pulp imaging. First, optical signals obtained through enamel and dentine may not reliably represent the condition of the entire pulp, particularly in teeth with thick dentine, extensive restorations, calcification, or complex root anatomy. Second, inflammation may alter local vascular and cellular responses without causing complete tissue death, making it difficult to establish universal spectral thresholds for irreversible pulpitis or necrosis. Third, mixed states of inflammation and necrosis may produce overlapping spectral patterns that complicate automated classification.

Future studies should therefore recruit clinically diverse populations, include different tooth types and disease severities, and use blinded assessment with independent validation datasets. Researchers should also investigate whether combining multispectral imaging with clinical findings and molecular biomarkers improves diagnostic performance over conventional testing alone. The relationship between inflammatory activity, tissue survival, and reparative potential is especially important because inflammation does not automatically eliminate the possibility of healing (Yu & Abbott, 2007; Goldberg et al., 2015). Research on photobiomodulation and pulp-regenerative endodontics further highlights the importance of understanding viable tissue responses when evaluating pulp-preservation strategies (Yong et al., 2023).

Overall, multispectral imaging represents a promising investigational approach to pulp vitality assessment, but its diagnostic value will depend on standardized acquisition protocols, biologically meaningful spectral features, reliable reference standards, and prospective clinical validation. Demonstrating that the technology can consistently distinguish inflamed but viable pulp from necrotic tissue would represent an important step toward more accurate diagnosis and evidence-based preservation of dental pulp.

CLINICAL IMPLICATIONS, LIMITATIONS, AND FUTURE DIRECTIONS

Clinical Implications

Multispectral imaging may improve endodontic diagnosis by providing additional information about pulpal tissue characteristics beyond the neural responses measured by conventional sensibility tests. Distinguishing inflamed but viable pulp from necrotic pulp is clinically important because the presence of inflammation does not necessarily indicate complete loss of vitality or eliminate the possibility of successful vital pulp therapy. Traditional diagnostic approaches may not accurately reflect the biological status of the entire pulp tissue, particularly when inflammation and necrosis occur in different regions of the same tooth (Sigurdsson, 2003; Abbott & Yu, 2007). Consequently, multispectral imaging could complement clinical examination by identifying wavelength-dependent optical patterns potentially associated with tissue perfusion, oxygenation, and structural alterations. The potential role of such nontraditional approaches in improving pulp vitality assessment has been highlighted by Afkhami et al. (2024).

Table 3: Proposed Diagnostic Workflow and Clinical Validation Framework for Multispectral Pulp Imaging

Workflow stage	Principal procedure	Diagnostic objective	Validation requirement
1. Clinical assessment	Review symptoms, dental history, sensibility tests, and radiographs	Establish the initial clinical diagnosis	Compare findings with established diagnostic criteria
2. Image acquisition	Capture multispectral images at standardized wavelengths	Obtain optical information related to pulpal tissue characteristics	Assess image quality and measurement repeatability
3. Image preprocessing	Correct illumination variability, noise, and background interference	Improve spectral data consistency	Evaluate preprocessing stability across samples
4. Feature extraction	Identify relevant spectral patterns and signal characteristics	Detect potential indicators of perfusion, oxygenation, and tissue changes	Assess feature reliability and biological relevance
5. Classification	Apply validated statistical or machine-learning models	Categorize pulp as viable and inflamed, likely necrotic, or indeterminate	Measure sensitivity, specificity, and classification agreement
6. Reference comparison	Compare predictions with appropriate clinical, histological, or outcome evidence	Establish diagnostic validity	Use predefined reference standards and independent validation
7. Clinical integration	Interpret imaging alongside conventional examinations	Support appropriate treatment planning	Assess clinical utility, safety, and effects on treatment decisions

Source: Proposed framework synthesized from Afkhami et al. (2024), Abbott and Yu (2007), Bhat et al. (2024), and Zanini et al. (2017). The workflow is conceptual and requires prospective clinical testing.

Clinically, improved differentiation between viable and necrotic pulp could support more appropriate treatment decisions, including pulp preservation, pulpotomy, root canal treatment, and further diagnostic investigation. Evidence indicates that vital pulp therapy may achieve favourable outcomes in selected permanent teeth diagnosed with irreversible pulpitis, depending on the biological condition of the remaining pulp, treatment procedures, and case selection (Kahler et al., 2023; Lin et al., 2020). Therefore, multispectral imaging could potentially help clinicians identify cases in which viable tissue remains despite significant inflammatory symptoms. However, imaging findings should be interpreted alongside clinical symptoms, examination results, and other relevant diagnostic evidence rather than being used as an independent determinant of treatment.

LIMITATIONS

Despite its potential, multispectral imaging presents several technical and biological limitations. Optical signals obtained from dental tissues may be influenced by enamel thickness, dentine characteristics, tooth pigmentation, restorations, light scattering, and the limited penetration of selected wavelengths. These factors may reduce the reliability of measurements and complicate comparisons between individual teeth. Furthermore, inflammation and necrosis are not always uniform throughout the pulp. A tooth may contain viable, inflamed, and necrotic regions simultaneously, meaning that a single optical measurement may fail to represent the condition of the entire tissue. The complex biological responses of the dental pulp to injury further complicate diagnosis because inflammation may coexist with reparative activity and residual tissue viability (Yu & Abbott, 2007; Goldberg et al., 2015; El Karim et al., 2021).

Another limitation concerns the lack of established multispectral imaging protocols, validated diagnostic thresholds, and extensive clinical evidence specifically demonstrating its ability to distinguish inflamed viable pulp from necrotic pulp. Although nontraditional pulp vitality assessment methods are being explored, their clinical usefulness depends on reproducibility, diagnostic accuracy, and validation against appropriate reference standards (Afkhami et al., 2024). In addition, inflammatory biomarkers and molecular indicators of cell death may provide complementary evidence, but their interpretation also requires consideration of disease severity, sampling methods, and the relationship between local biological changes and clinical symptoms (Zanini et al., 2017; Lennon, 2024). Current strategies for diagnosing irreversible pulpitis similarly demonstrate the need for improved methods that reflect underlying tissue biology more accurately (Bhat et al., 2024).

FUTURE DIRECTIONS

Future research should prioritize the development of standardized multispectral imaging systems capable of

measuring reproducible optical responses across different tooth types and clinical conditions. Experimental studies should investigate suitable wavelengths, illumination methods, sensor configurations, and image-processing procedures for detecting changes associated with pulpal perfusion and tissue viability. Clinical investigations should compare multispectral findings with conventional sensibility tests, clinical classifications, relevant biological indicators, and appropriate reference standards. Diagnostic performance should be assessed using sensitivity, specificity, predictive values, reproducibility, and external validation across diverse patient populations. These investigations would help establish whether multispectral imaging offers meaningful diagnostic advantages over existing approaches (Afkhami et al., 2024; Abbott & Yu, 2007).

Artificial intelligence and machine learning represent additional opportunities for advancing this technology. Algorithms could be trained to recognize complex spectral patterns and distinguish among healthy pulp, inflamed viable pulp, partially necrotic pulp, and complete pulp necrosis. The application of machine learning to hyperspectral imaging has demonstrated potential for identifying subtle patterns in other biological and agricultural settings, although these findings cannot be directly generalized to dental pulp without specific validation (Velásquez et al., 2024). Future systems could also integrate multispectral measurements with clinical symptoms, radiographic findings, and molecular biomarkers to produce more comprehensive diagnostic assessments. Research into photobiomodulation and pulp-regenerative endodontics may further inform investigations of tissue preservation and healing, although therapeutic responses should remain distinct from diagnostic evidence (Yong et al., 2023).

Ultimately, prospective clinical trials, standardized reporting, and long-term treatment-outcome studies are required before multispectral imaging can be recommended for routine endodontic diagnosis. Its future value will depend on demonstrating that it can reliably identify viable pulp tissue, improve treatment selection, and reduce unnecessary removal of tissue with healing potential while avoiding inappropriate preservation of irreversibly damaged or necrotic pulp (Torabinejad & Shabahang, 2009; Kahler et al., 2023).

CONCLUSION

Multispectral imaging represents a promising approach for improving the differentiation of inflamed but viable dental pulp from necrotic pulp. Conventional diagnostic methods have limitations because sensibility tests primarily evaluate neural responses rather than directly measuring pulpal blood flow and tissue viability. Consequently, integrating optical imaging techniques with established clinical assessments may provide a more comprehensive understanding of pulpal status (Sigurdsson, 2003; Abbott & Yu, 2007; Afkhami et al., 2024). By evaluating wavelength-dependent tissue signals associated with oxygenation, perfusion, and structural changes, multispectral imaging may support more objective diagnostic

decisions, although its clinical accuracy requires further investigation.

Accurate differentiation is particularly important because inflammation does not necessarily indicate complete loss of pulp vitality or eliminate the possibility of healing. Evidence concerning vital pulp therapy emphasizes the importance of understanding the biological condition of the remaining pulp tissue when selecting treatment strategies (Goldberg et al., 2015; Lin et al., 2020; Kahler et al., 2023). The inflammatory and reparative responses of the pulp further demonstrate the need to distinguish tissue injury from irreversible tissue destruction (Yu & Abbott, 2007; El Karim et al., 2021). Therefore, multispectral imaging could contribute to improved treatment planning by helping clinicians identify potentially preservable pulp tissue while supporting the recognition of necrotic conditions (Torabinejad & Shabahang, 2009; Zanini et al., 2017).

Future developments may involve integrating multispectral imaging with artificial intelligence, machine learning, and molecular biomarkers to improve the interpretation of complex diagnostic patterns (Bhat et al., 2024; Lennon, 2024). The potential contribution of advanced optical analysis and machine learning is also illustrated by research applying hyperspectral imaging to early disease detection in agricultural systems, although such findings cannot be directly extrapolated to dental pulp diagnosis (Velásquez et al., 2024). Furthermore, advances in pulp regeneration and photobiomodulation highlight the importance of accurate biological assessment in developing tissue-preserving treatment approaches (Yong et al., 2023).

Ultimately, prospective clinical studies are required to establish standardized imaging protocols, diagnostic thresholds, sensitivity, specificity, and reproducibility across different tooth types and clinical conditions. Multispectral imaging should therefore be regarded as a developing diagnostic technology rather than an established replacement for conventional assessment. Its successful clinical application could improve the differentiation of inflamed viable pulp from necrotic pulp, strengthen evidence-based endodontic decision-making, and support the preservation of natural dental tissues.

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