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Pulp Vitality Testing: A Review of Current Methods and Emerging Technologies

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ABSTRACT

Accurate assessment of pulp vitality is fundamental in endodontic diagnosis and treatment planning, as it directly influences therapeutic decisions and long-term outcomes. Traditional sensibility tests, such as thermal and electric pulp testing, remain widely used in clinical practice due to their accessibility and ease of application. However, these methods measure neural responses rather than true vascular vitality, and are prone to false-positive or false-negative outcomes, particularly in teeth with immature apices, extensive restorations, or trauma. Recent advances have shifted focus toward vascular-based vitality assessment, utilizing technologies such as pulse oximetry, laser Doppler flowmetry, and photoplethysmography, which evaluate pulpal blood flow as a more direct indicator of pulp health. Emerging optical modalities, biosensors, and artificial intelligence–enhanced diagnostic systems further highlight the future of pulp testing, with the potential to improve accuracy, reproducibility, and clinical utility. This review synthesizes the current evidence on conventional and emerging pulp vitality testing methods, discusses their respective strengths and limitations, and explores future directions in developing reliable, patient-friendly, and standardized diagnostic strategies.

Keywords: pulp vitality, pulp testing, electric pulp test, thermal test, pulse oximetry, laser Doppler flowmetry, photoplethysmography, dental diagnostics

1. INTRODUCTION

Accurate diagnosis of pulpal health status remains one of the most critical steps in endodontic practice. The ability to differentiate between a vital and a non-vital pulp directly determines the choice of treatment, ranging from conservative pulp preservation procedures to root canal therapy or extraction. Despite being fundamental, the assessment of pulp vitality continues to present clinical challenges, as the pulp is encased in mineralized tissues and inaccessible to direct visual or tactile evaluation.

Traditionally, clinicians have relied on indirect tests that measure neural response to stimuli, commonly referred to as sensibility tests. These include thermal tests (cold and heat) and the electric pulp test, both of which trigger sensory responses that are presumed to reflect pulpal health. While widely used for decades, these tests do not measure true vitality defined as the presence of an intact vascular supply within the pulp and their accuracy can be compromised in cases of trauma, immature teeth, or heavily restored crowns.

With advancements in diagnostic technology, there is increasing emphasis on vascular-based testing modalities, which aim to measure pulpal blood flow directly. These innovations include pulse oximetry, laser Doppler flowmetry, and more recently, optical coherence tomography and photoplethysmography. The integration of biosensor technologies and artificial intelligence is also emerging, offering potential to improve diagnostic reliability and clinical decision-making.

This review provides a comprehensive overview of current methods for pulp vitality testing, evaluates their diagnostic accuracy and clinical relevance, and highlights emerging technologies that may redefine standard diagnostic approaches. By exploring both established and novel methods, the paper aims to provide clinicians and researchers with a synthesized perspective on the evolving landscape of pulp vitality diagnostics.

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2. 2. PHYSIOLOGY & DIAGNOSTIC PRINCIPLES

The pulp is a specialized soft tissue encased within rigid dentin and enamel, comprising connective tissue, nerves, and a vascular network. Its vitality depends primarily on the integrity of the blood supply, which is delivered through the apical foramen. The vascular system ensures oxygenation, nutrient delivery, and waste removal, playing a central role in maintaining pulpal health and repair potential.

Two fundamental aspects form the basis of pulp testing: sensibility and vitality.

- Pulp sensibility refers to the pulp's ability to respond to external stimuli, typically mediated through sensory nerve fibers, such as Aδ and C fibers. Sensibility tests, including thermal and electric methods, are designed to activate these fibers, producing a subjective patient response.
- Pulp vitality, in contrast, refers to the actual health of the pulp tissue, specifically its vascular supply. As vascular integrity is a more reliable indicator of pulp status than nerve response, vitality tests aim to assess blood flow or oxygen saturation within the pulp chamber.

Clinical misinterpretation often arises because sensibility tests may yield false responses. For example, a tooth with an inflamed pulp may respond exaggeratedly to cold, while a recently traumatized tooth with intact blood supply may fail to respond due to transient neural disruption. Similarly, heavily restored teeth or those with calcified canals may interfere with accurate stimulus conduction.

Vitality tests, by directly measuring pulpal circulation, attempt to overcome these limitations. Laser Doppler flowmetry and pulse oximetry represent key examples, offering objective measurements of vascular status. However, these methods also face practical challenges, including equipment costs, operator training, and technical difficulties in isolating pulpal signals from surrounding tissues.

An understanding of these physiological and diagnostic principles is essential for clinicians to interpret test results accurately, select appropriate testing modalities, and integrate findings into comprehensive treatment planning. The distinction between sensibility and vitality testing underscores the ongoing need for more reliable and standardized diagnostic tools in endodontics.

3. 3. CONVENTIONAL SENSIBILITY TESTS

Conventional pulp testing relies on the assessment of neural response to external stimuli, and these methods have been the mainstay in clinical practice for decades due to their simplicity, low cost, and accessibility. They are designed to elicit a subjective response from the patient, reflecting the excitability of sensory nerve fibers within the pulp rather than true vitality

3.1. 3.1 Thermal Tests

Thermal stimulation is one of the most commonly used diagnostic tools.

1.0.1. Cold tests

These include the use of refrigerant sprays (e.g., 1,1,1,2-tetrafluoroethane), carbon dioxide snow, or ice sticks applied to the tooth surface. Cold stimulates Aδ fibers, producing a sharp, short-lasting response in vital pulps. Cold testing is generally considered more reliable than heat, with reported higher sensitivity for detecting pulpal necrosis.

1.0.2. Heat tests

Commonly conducted using heated gutta-percha sticks or hot water. These tests stimulate C fibers and are less frequently employed due to patient discomfort and risk of damaging restorative materials. Heat testing is typically reserved for cases with suspected irreversible pulpitis, where spontaneous heat-induced pain is a key clinical feature.

3.2. 3.2 Electric Pulp Testing (EPT)

The electric pulp tester delivers a small electrical current to the tooth surface, stimulating Aδ fibers in the pulp. The patient signals perception of sensation, which is recorded as a positive response.

Advantages

Easy to use, reproducible, and capable of detecting nerve function even in teeth with thick enamel or dentin.

Limitations

False positives may occur in cases of conduction through metallic restorations or periodontal tissues, while false negatives may result from recently traumatized teeth, immature apices, or calcified canals. Additionally, EPT does not provide information on the degree of pulpal inflammation.

3.3. 3.3 Clinical Considerations

Although widely used, sensibility tests should be interpreted cautiously. Their reliance on subjective patient reporting introduces variability, and they cannot distinguish between reversible and irreversible pulpitis. Combining multiple sensibility tests improves diagnostic accuracy and should be integrated with clinical findings, radiographs, and patient history to form a comprehensive diagnosis.

4. 4. VASCULAR-BASED VITALITY TESTS

Vascular-based vitality tests focus on the direct measurement of pulpal blood flow or oxygenation, providing a more objective and reliable assessment of pulp health compared to neural-based methods. These tests represent a significant shift in diagnostic philosophy, as vascular integrity is a definitive marker of vitality.

4.1. 4.1 Pulse Oximetry

Pulse oximetry measures oxygen saturation within pulpal blood using light absorption principles. Adapted dental probes are applied to the tooth surface, and differential absorption of red and infrared light indicates oxygen saturation.

Strengths

Non-invasive, objective, and comparable to medical oximetry principles.

Limitations

Difficulties with probe adaptation, interference from tooth structure, and limited device availability hinder routine use.

4.2. 4.2 Laser Doppler Flowmetry (LDF)

LDF utilizes a low-power laser directed into the tooth; the reflected light undergoes frequency shifts when interacting with moving red blood cells, allowing quantification of blood flow.

Strengths

Provides continuous, non-invasive measurement of pulpal blood flow.

Limitations

Sensitive to movement artifacts and contamination by signals from gingival or periodontal tissues. Requires specialized equipment and operator expertise.

4.3. 4.3 Photoplethysmography (PPG) and Near-Infrared Spectroscopy (NIRS)

Emerging modalities such as PPG and NIRS use optical sensors to detect blood volume changes and oxygenation in the pulp.

Strengths

Potentially more portable and adaptable for dental applications compared to LDF.

Limitations

Currently experimental, with limited clinical validation and standardization.

4.4. 4.4 Clinical Implications

Vascular-based methods offer greater diagnostic accuracy than sensibility tests, particularly in traumatized, immature, or heavily restored teeth. However, their adoption is limited by cost, equipment complexity, and lack of standard clinical protocols. Continued development of user-friendly, chairside devices is essential for their integration into everyday practice.

5. 5. IMAGING & ADVANCED OPTICAL METHODS

Advances in optical and imaging technologies have opened new possibilities for pulp vitality assessment beyond traditional sensibility and vascular tests. These methods aim to provide real-time, high-resolution insights into pulpal blood flow and tissue integrity.

5.1. 5.1 Optical Coherence Tomography (OCT)

OCT provides cross-sectional imaging of dental tissues by analyzing light backscattering. Modified OCT systems can visualize pulpal microcirculation and assess structural integrity non-invasively.

Strengths

High-resolution, non-ionizing, and capable of detecting pulpal vascular patterns.

Limitations

Still in early clinical application, with significant equipment costs and limited accessibility.

5.2. 5.2 Hyperspectral Imaging

This method captures reflectance data across a wide spectrum of wavelengths to differentiate tissues based on oxygenation and biochemical composition. Hyperspectral imaging has shown promise in detecting pulpal vitality through non-contact measurements.

Strengths

Potential for non-invasive chairside application.

Limitations

Currently confined to research, requiring further validation and miniaturization.

5.3. 5.3 Contrast-Enhanced Imaging

Experimental approaches using contrast agents and advanced imaging modalities (e.g., micro-computed tomography, MRI) have been explored in research contexts for detailed visualization of pulpal vasculature. These methods, while informative, are not practical for routine clinical use.

5.4. 5.4 Future Perspectives

Advanced optical technologies may complement or even replace existing tests by offering non-invasive, objective, and reproducible data. Integration with artificial intel-

Table 1: Comparative Evidence on Pulp Vitality Testing Methods

Method	Principle	Measures	Strengths	Limitations	Clinical Use
Cold Test	Application of refrigerant/ CO□	Neural response (Aδ fibers)	Simple, inexpensive, widely available	Subjective, false positives/negatives, cannot assess blood flow	Routine first-line test
Heat Test	Application of heated material	Neural response (C fibers)	Useful in suspected irreversible pulpitis	Less reliable, uncomfortable, potential damage to restorations	Adjunctive, selective use
Electric Pulp Test (EPT)	Low electrical current	Neural response (Aδ fibers)	Easy to use, reproducible	Subjective, affected by trauma, immature teeth, restorations	Routine use with caution
Pulse Oximetry	Light absorption (red/infrared)	Oxygen saturation	Objective, non-invasive, direct vitality measure	Probe adaptation challenges, equipment availability	Research/limited clinical use
Laser Doppler Flowmetry (LDF)	Laser light frequency shift from RBCs	Blood flow	Continuous, objective measurement	Expensive, motion artifacts, technical expertise required	Research/limited clinical use
Photoplethysmography (PPG)/NIRS	Optical detection of blood volume/ oxygenation	Vascular changes	Portable potential, non-invasive	Early research stage, limited validation	Experimental
Optical Coherence Tomography (OCT)	Light backscatter imaging	Structural/vascular data	High-resolution, non-ionizing	Expensive, not yet standardized	Research stage
Hyperspectral Imaging	Spectral reflectance analysis	Tissue oxygenation/ biochemical profile	Non-contact, emerging	Limited validation, experimental	Research stage

ligence and automated signal processing may further enhance their diagnostic accuracy, enabling earlier and more reliable detection of pulp pathology.

Table 1. Comparison of Pulp Vitality Testing Methods

6. 6. BIOSENSORS, BIOMARKERS & POINT-OF-CARE APPROACHES

Beyond functional testing, there is growing interest in the use of biosensors and biomarkers to assess pulp vitality. These approaches aim to detect biochemical changes associated with pulp inflammation, degeneration, or vitality, offering an adjunct or alternative to neural and vascular-based tests.

6.1. 6.1 Salivary and Gingival Crevicular Fluid Biomarkers

Saliva and gingival crevicular fluid (GCF) contain inflammatory mediators such as interleukins (IL-6, IL-8), tumor necrosis factor-alpha (TNF-α), and matrix metalloproteinases (MMPs). Elevated levels of these biomarkers have been associated with pulpal inflammation and periapical disease.

Strengths

Non-invasive collection, potential for early detection of disease activity.

Limitations

Lack of specificity, as inflammatory mediators may originate from periodontal or systemic sources.

6.2. 6.2 Pulp Tissue and Dentin Biomarkers

Direct pulp exposure (e.g., during selective caries removal) can provide access to dentinal fluid and pulpal tissue, which may contain biomarkers of vitality and inflammation. However, this approach is invasive and not suitable for routine diagnostics.

6.3. 6.3 Biosensor and Lab-on-a-Chip Technologies

Point-of-care biosensors are being developed to rapidly analyze small volumes of oral fluid for diagnostic markers. Lab-on-a-chip devices, integrating microfluidics with electrochemical or optical sensors, offer portable, chairside potential for pulp vitality diagnostics.

Strengths

Rapid, minimally invasive, objective.

Limitations

Still experimental, requiring validation, standardization, and cost reduction before clinical use.

Biosensor technologies may eventually provide clinicians with biochemical evidence of pulp status, complementing existing functional tests for a more holistic diagnostic strategy.

7. 7. ARTIFICIAL INTELLIGENCE AND SIGNAL PROCESSING

Artificial intelligence (AI) and advanced signal processing are emerging as powerful tools for improving the accuracy and reproducibility of pulp vitality testing.

7.1. 7.1 AI for Signal Interpretation

AI algorithms, particularly machine learning models, have been applied to interpret signals from laser Doppler flowmetry, photoplethysmography, and pulse oximetry. By filtering noise and identifying subtle patterns, AI can enhance diagnostic reliability and reduce operator dependency.

7.2. 7.2 Automated Image and Spectral Analysis

Optical modalities such as OCT and hyperspectral imaging generate complex data sets. Deep learning algorithms have been successfully trained to classify tissue vitality from these images, potentially enabling real-time, automated pulp status assessment.

7.3. 7.3 Integration into Clinical Workflow

AI-driven platforms may integrate data from multiple sources, sensibility tests, vascular-based devices, biomarkers, and imaging to provide a multimodal diagnostic decision support system. Such integration has the potential to minimize subjective interpretation, standardize diagnostics, and improve patient outcomes.

Despite promising results, AI applications in pulp vitality assessment remain at the research stage. Large-scale clinical validation and regulatory approval will be necessary before these technologies become part of routine practice.

8. 8. COMPARATIVE PERFORMANCE & EVIDENCE SYNTHESIS

A range of pulp testing methods are available, each with distinct strengths and limitations. Conventional sensibility tests remain the most commonly used due to their simplicity, despite their limited accuracy in certain clinical contexts. Vascular-based tests provide more direct evidence of vitality but face barriers of cost and complexity. Biosensor and AI-enhanced approaches represent the future, but are still largely confined to laboratory or pilot clinical studies.

8.1. Evidence Summary

Systematic reviews and diagnostic accuracy studies suggest the following trends:

Cold testing

has the highest sensitivity among sensibility tests, though it is subject to false positives in inflamed pulps.

Electric pulp testing

provides reproducibility but is limited in immature or traumatized teeth.

Pulse oximetry and LDF

consistently show higher accuracy in distinguishing vital from non-vital pulps, although practical application is limited.

Emerging optical methods

(OCT, hyperspectral imaging) and biosensors demonstrate strong experimental potential, but lack sufficient clinical trials for routine adoption.

Values represent preliminary ranges from early pilot studies, requiring further validation.

9. 9. CLINICAL RECOMMENDATIONS & PRACTICAL CONSIDERATIONS

The selection of pulp vitality testing methods in clinical practice must balance diagnostic accuracy, practicality, and patient comfort. Conventional sensibility tests particularly cold and electric pulp tests remain indispensable first-line approaches due to their simplicity, affordability, and widespread availability. However, clinicians should recognize their inherent limitations, especially in cases involving immature teeth, traumatized teeth, or calcified

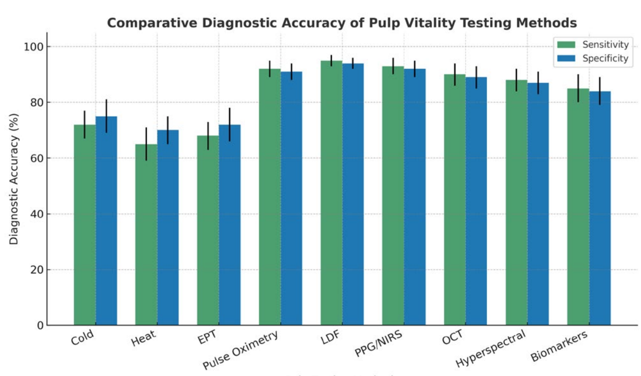

Figure 1 : Comparative Diagnostic Accuacy of Vitalley Testing Methods

Table 2 : Comparative Evidence on Pulp Vitality Testing Methods

Method	Sensitivity Range	Specificity Range	Reliability	Clinical Applicability	Key Limitations
Cold Test	0.72–0.95	0.65–0.90	Moderate–High	Widely available, first-line	False positives in inflamed teeth, subjective
Heat Test	0.60–0.80	0.70–0.85	Moderate	Selective use in suspected irreversible pulpitis	Patient discomfort, limited accuracy
Electric Pulp Test	0.70–0.90	0.75–0.90	Moderate	Routine adjunct test	False negatives in immature/ traumatized teeth
Pulse Oximetry	0.85–0.98	0.85–0.97	High	Research/early clinical use	Equipment adaptation, cost
Laser Doppler Flowmetry	0.80–0.95	0.85–0.95	High	Research/early clinical use	Motion artifacts, equipment cost
Photoplethysmography/ NIRS	0.80–0.90	0.80–0.90	Experimental	Emerging, portable potential	Limited clinical validation
OCT	0.85–0.95	0.85–0.95	Experimental	High-resolution imaging potential	Expensive, early research
Hyperspectral Imaging	0.80–0.90	0.80–0.90	Experimental	Non-contact, non-invasive	Research only
Biomarker/Biosensor	Variable	Variable	Experimental	Future adjunct tool	Lack of standardization, specificity issues

canals. In such contexts, reliance solely on sensibility tests may lead to misdiagnosis, risking overtreatment or undertreatment.

Where available, vascular-based vitality tests such as pulse oximetry or laser Doppler flowmetry provide more physiologic evidence of pulp status and may be particularly useful in equivocal cases, such as traumatic dental injuries or when monitoring pulp healing after regenerative endodontic procedures. Advanced imaging techniques (e.g., OCT, hyperspectral imaging) and biosensor-based assays, though not yet mainstream, show promise as adjunctive methods that may soon enhance diagnostic decision-making.

From a practical standpoint, integration of multiple methods, sensibility, vascular-based, and emerging diagnostic tools offers a more comprehensive assessment than any single test alone. Clinicians are advised to interpret test outcomes within the broader clinical and radiographic context, incorporating patient history, symptoms, and periapical findings.

10. 10. LIMITATIONS OF CURRENT EVIDENCE

Despite considerable progress, several limitations restrict the current evidence base for pulp vitality testing. First, diagnostic accuracy studies often suffer from methodological heterogeneity, with variable reference standards, patient populations, and outcome definitions. This complicates comparisons across studies and reduces generalizability. Many studies also employ small sample sizes and lack long-term follow-up, limiting insights into prognostic value.

Furthermore, while vascular-based and optical methods show superior accuracy in controlled research settings, their translation into routine practice is hindered by equipment costs, operator training requirements, and sensitivity to motion or artifact. Biosensor and biomarker-based approaches, though conceptually appealing, remain in early developmental stages, with little standardization of sampling protocols or biomarker panels.

Another limitation lies in the scarcity of head-to-head trials comparing conventional and advanced modalities under real-world conditions. Most evidence stems from pilot studies or laboratory-based research, highlighting the need for robust multicenter trials and systematic reviews with standardized diagnostic accuracy metrics.

11. 11. FUTURE PERSPECTIVES

The future of pulp vitality diagnostics lies in the convergence of physiological, biochemical, and computational approaches. Vascular-based methods such as pulse oximetry are likely to gain broader clinical adoption as device designs become more portable, user-friendly, and cost-effective. Parallel advances in optical imaging (e.g., OCT, hyperspectral imaging) are expected to yield non-invasive, high-resolution tools capable of directly visualizing pulpal vascular responses.

The emergence of biosensors and lab-on-a-chip systems may enable chairside detection of pulp-specific biomarkers, providing objective biochemical evidence to complement functional tests. Integration with artificial intelligence promises to further enhance accuracy by processing complex multimodal data, filtering noise, and delivering real-time diagnostic recommendations.

Importantly, future research should focus on developing standardized protocols, validating novel technologies through large-scale clinical trials, and assessing cost-effectiveness for routine practice. Multimodal diagnostic platforms that combine sensibility, vascular, biochemical, and AI-driven data streams may ultimately redefine pulp vitality assessment, moving the field toward precision endodontic diagnostics.

12. 12. CONCLUSION

Pulp vitality testing remains a cornerstone of endodontic diagnosis, guiding treatment planning and prognosis. Conventional sensibility tests—particularly cold and electric pulp testing—continue to dominate clinical practice due to their accessibility, despite recognized limitations in specificity and accuracy. Vascular-based methods, including pulse oximetry and laser Doppler flowmetry, provide more direct physiologic insights and show superior diagnostic potential, though their routine use is constrained by cost and technical complexity.

Emerging diagnostic modalities, such as optical coherence tomography, hyperspectral imaging, and biosensor-based assays, herald a future where pulp vitality assessment may become more objective, non-invasive, and precise. Artificial intelligence and multimodal signal processing are poised to further enhance diagnostic reliability by integrating data across neural, vascular, and biochemical domains.

Nevertheless, translation of these innovations into widespread practice requires rigorous validation, standardization of methodologies, and evaluation of cost-effectiveness. A pragmatic, multimodal approach integrating traditional sensibility tests with advanced physiologic and biochemical measures appears most promising for improving diagnostic accuracy and patient outcomes. Ultimately, future progress in pulp vitality testing will not only refine diagnostic precision but also support more conservative, biologically based endodontic care.

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