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Modern aspects of the use of hardware methods for diagnosing pulp vitality (Part 1. Traditional methods)

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Abstract

INTRODUCTION. Diagnosis of pulp diseases remains a pressing issue in dentistry, which is determined by their high prevalence and, in some cases, latent course.

AIM. To study new technologies developed for hardware testing of pulp vitality based on modern literature data.

MATERIALS AND METHODS. A systematic search was performed in the electronic databases PubMed, Google Scholar, eLibrary, Google Patents. The search depth was 6 years – from 2019 to 2024.

RESULTS. The search in the electronic library databases initially yielded 793 results. After screening titles and abstracts and removing duplicates, 368 articles were identified, assessed by reading their full text, and analysis of whether the publication criteria were met; 65 articles were included in the systematic review. Based on the results preliminary screening and application of the eligibility criteria, 15 publications were included in the qualitative analysis and 7 publications in the quantitative analysis, 43 publications were used to write the introduction text and in the discussion of the study results. Based on the patent search, 4 patents were included in the analysis. Most of the well-conducted and documented studies were devoted to the pulse oximetry method.

CONCLUSIONS. An analysis of modern literature sources showed that the most common methods for assessing pulp vitality are laser Doppler flowmetry and pulse oximetry. Pulse oximetry is the most accurate diagnostic tool. Alternative diagnostic methods are increasingly being explored for their potential to assess pulp vitality. The most frequently mentioned methods in scientific publications for 2019–2024 are: ultrasound Doppler flowmetry, transillumination, magnetic resonance imaging, speckle imaging, tooth temperature measurements, electroodontometry and plethysmography. However, to date, none of the alternative methods for diagnosing pulp vitality have been integrated into clinical practice, indicating an ongoing challenge in creating a reliable approach to assessing pulp vitality.

Keywords: hardware methods, diagnostics, pulp vitality

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Современные аспекты использования аппаратных методов диагностики витальности пульпы (Часть 1. Традиционные методы)

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Резюме

ВВЕДЕНИЕ. Диагностика болезней пульпы остается актуальной проблемой в стоматологии, что определяется их высокой распространенностью и в ряде случаев скрытым течением.

ЦЕЛЬ ИССЛЕДОВАНИЯ. Изучение по данным современной литературы новых технологий, разработанных для аппаратного тестирования витальности пульпы.

МАТЕРИАЛЫ И МЕТОДЫ. Систематический поиск был выполнен в электронных базах данных PubMed, Google Scholar, eLibrary, Google Patents. Глубина поиска составила 6 лет – с 2019 по 2024 г.

РЕЗУЛЬТАТЫ. Поиск в базах электронных библиотек первоначально дал 793 результата. После изучения названий и аннотаций, и удаления дубликатов было идентифицировано 368 статей, оцененных путем прочтения их полного текста, и анализа соответствия критериям включения публикации в исследование 65 статей были включены в систематический обзор. По результатам предварительного просмотра и применения критериев приемлемости 15 публикаций были включены в качественный анализ и 7 публикаций в количественный анализ, 43 публикаций были использованы для написания текста введения и при обсуждении результатов исследования. По результатам патентного поиска в анализ включены 4 патента. Большинство качественно проведенных и задокументированных исследований посвящено методу пульсоксиметрия.

ВЫВОДЫ. Анализ современных источников литературы показал, что наиболее часто витальность пульпы оценивается с помощью методов лазерной допплеровской флоуметрии и пульсоксиметрии. При этом пульсоксиметрии является наиболее точным диагностическим инструментом. Нетрадиционные методы диагностики все чаще исследуются на предмет их потенциала для оценки витальности пульпы. Наиболее часто в научных публикациях за 2019–2024 гг. упоминаются: ультразвуковая допплеровская флоуметрия, трансиллюминация, магнитно-резонансная томография, спекл-визуализация, измерения температуры зубов, электроодонтометрия и плетизмография**.** Однако на сегодняшний день ни один из нетрадиционных методов диагностики витальности пульпы не интегрирован в клиническую практику, что указывает на продолжающуюся проблему создания надежного подхода к оценке витальности пульпы.

Ключевые слова: аппаратные методы, диагностика, витальность пульпы

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INTRODUCTION

Oral diseases are among the most prevalent noncommunicable conditions affecting individuals throughout their lives [1]. Among patients examined within healthcare systems, 25% have been diagnosed with pulp and periapical tissue diseases [2]. The prevalence of symptomatic pulpitis is considered high, making it the most common cause of orofacial pain and the leading reason for seeking emergency dental care [3]. However, estimating the true prevalence of pulpitis is challenging, as up to 40% of pulp inflammations may progress to necrosis without any clinical symptoms [4]. Consequently, the diagnosis and treatment of pulp diseases remain major challenges in dentistry, largely due to their high prevalence in the general population [2; 5–7].

With the advancement of contemporary endodontics, vital pulp therapy (VPT) has gained increasing importance [8; 9]. Determining pulp vitality is essential for the diagnosis of pulp diseases and for timely, optimal treatment. Nevertheless, despite a substantial body of research, evidence-based diagnostic methods remain insufficient [10].

Histological examination is regarded as the gold standard in endodontics. However, clinical assessment of the dental pulp through histological methods is not feasible, as the pulp cannot be directly visualized unless it is exposed [11]. Therefore, methods assessing pulp sensitivity and vitality are typically employed in clinical practice.

During routine dental examinations, clinicians most commonly use electric pulp tests, thermal tests, and cavity preparation tests, all of which are classified as pulp sensitivity tests [11]. These are based on the fact that the pulp–dentin complex is richly innervated by sensory fibers, predominantly A-delta and C fibers [12]. Most sensitivity tests rely on the stimulation of these nerve fibers. Loss of sensory function in the pulp results in negative responses to thermal and electric pulp tests [12].

However, pulp sensitivity tests may exacerbate pain in patients, and their subjectivity is influenced by individual pain thresholds, anxiety, and emotional stress [13]. Moreover, these tests only indirectly assess pulp vitality by evaluating neural response, without accounting for vascular supply. As a result, false-negative outcomes may occur in teeth that have lost sensory function but retain an intact vascular system, which actually indicates that the pulp is still vital [14].

The limitations of sensitivity testing have led to the development of pulp vitality tests, which assess blood flow and oxygen saturation independently of the patient's response, providing a more accurate assessment of pulp status [15; 16]. Laser Doppler flowmetry (LDF) and pulse oximetry (PO) are the most well-known methods for evaluating pulp vitality [17]. Pulse oximetry measures oxygen saturation within the pulp chamber using a noninvasive sensor, while Doppler flowmetry assesses vascular flow by detecting the "concentration and velocity of blood cells" [18].

Nonetheless, LDF and PO have not seen widespread clinical adoption due to several challenges, including high cost, lengthy procedures, technical complexity, and inconsistent results. Both methods are also affected by factors such as enamel and dentin thickness, the presence of pigmentation or discoloration, and extensive restorations. In addition, improper positioning of the probe may influence measurements and lead to diagnostic errors [17].

Consequently, researchers are increasingly focusing on alternative approaches for pulp vitality assessment. These include optical methods – photoplethysmography, laser speckle imaging, laser transmission flowmetry, spectrophotometry, optical reflectance vitality testing, transillumination, and light-induced fluorescence–as well as ultrasound Doppler flowmetry, photoacoustic imaging, magnetic resonance imaging, and tooth temperature measurement [17].

An ideal pulp testing method should be objective, accurate, reproducible, painless, noninvasive, harmless, simple to perform, cost-effective, and technique-insensitive [19]. However, no universally accepted modern technologies for pulp vitality diagnosis are currently available [7; 17; 20]. This is primarily due to the limited number of well-designed and properly executed clinical trials evaluating pulp vitality diagnostic devices [21], which hinders the ability to conduct high-quality meta-analyses and systematic reviews. In Russia, studies of sufficient methodological quality in this field are virtually nonexistent.

In the English-language literature, pulp vitality tests are most comprehensively reviewed in the following systematic analyses: L. Dotto et al., in an umbrella review encompassing 81 studies across 25 reports, examine the available literature on device-based pulp vitality testing methods, analyzing the mechanisms behind these technologies and summarizing experimental findings [22]; S. Patro et al., in a systematic review with meta-analysis (10 studies for qualitative synthesis and 5 included in the meta-analysis), assessed the diagnostic accuracy of pulp vitality and sensitivity tests [11]; and F. Afkhami et al. provided an in-depth review exclusively focusing on non-conventional methods and techniques for evaluating pulp vitality, incorporating 65 studies [17].

Despite the growing international interest in hardware-based alternatives to traditional pulp testing and the abundance of reviews on conventional pulp sensitivity tests [17; 23; 24], Russian-language literature lacks comprehensive overviews regarding the application of pulp vitality tests and their associated advantages and limitations. High-quality systematic reviews conducted in accordance with the PRISMA protocol for the period 2019–2024 are virtually absent in the accessible domestic literature.

In Russia, the most detailed literature review on modern diagnostic approaches to pulp status was published in 2020 by A.V. Mitronin et al. [25]. The authors presented current perspectives on minimally invasive diagnostic methods for assessing pulp status, highlighting the advantages and limitations of diagnostic tools and evaluating their clinical effectiveness based on both domestic and international sources. The 2022 article by I.O. Larichkina primarily addressed pulp sensitivity tests, with laser Doppler flowmetry being the only pulp vitality test considered [26]. In a 2023 study by A.V. Popov et al., the authors provided an overview of instrumental methods for assessing pulp blood flow, offering a comparative analysis and evaluating their applicability during orthodontic tooth movement [27].

Thus, despite the significant number of systematic reviews and meta-analyses dedicated to device-based pulp vitality assessment in the international literature, these methods remain insufficiently represented in Russian studies – highlighting the relevance of our research.

AIM

The aim of this study is to review the latest technologies developed for device-based pulp vitality testing based on current literature.

MATERIALS AND METHODS

Search Strategy

A systematic electronic search was conducted using international databases PubMed and Google Scholar, as well as the Russian scientific electronic library eLibrary. Patent searches were carried out via the Google Patents database. The search covered a six-year period from 2019 to 2024. Russian literature was defined as studies conducted in Russia and published in Russian journals.

The search query included the following keywords: diagnostic, instrumental methods, pulp vitality.

Inclusion Criteria

1. Articles published in Russian or English between 2019 and 2024.
2. Types of publications: scientific articles – including clinical research and experimental studies – as well as systematic reviews.
3. Full-text availability free of charge online.
4. Relevance to the research topic – device-based methods for pulp vitality diagnostics.

Exclusion Criteria

1. Type of publication: conference abstracts, proceedings, and dissertations.
2. Lack of full-text availability online.
3. Absence of analysis regarding the effectiveness of the method.
4. Studies focusing solely on pulp sensitivity assessment methods (e.g., thermal or electric pulp testing).

A stepwise screening process was applied for the selection of publications. After identifying sources, the titles and abstracts of potential studies were screened, and duplicates were excluded. Full-text articles were then reviewed in detail. The reference lists of all included studies were examined to identify additional relevant publications. The eligibility of each article in relation to the research objective was assessed based on three criteria: evaluation of the title, abstract, and full text.

Data Extraction

Each included article was analyzed to extract information on bibliometric characteristics, study methodology, and research outcomes. Extracted variables included: pulp vitality tests and measurement techniques; patient-related variables (sample size, age, and sex); number of samples (teeth); tooth type; and the specific methodology and device used for vitality assessment.

RESULTS

A search of electronic library databases yielded 793 results. After screening titles and abstracts and removing duplicates, 368 articles were identified for full-text assessment. Of these, 233 articles were excluded due to failure to meet the inclusion criteria. The remaining 65 full-text articles were included in the systematic review. Following preliminary screening and application of eligibility criteria, 15 publications were included in the qualitative analysis, and 7 in the quantitative analysis. An additional 43 publications were used to support the Introduction and Discussion sections of the study (Fig. 1).

To characterize traditional device-based methods for assessing pulp vitality, publications on the use of pulse oximetry (6 studies, of which 4 were included in the quantitative analysis) and laser Doppler flowmetry (3 studies) were reviewed. Among non-traditional methods, the review included 2 studies on photoplethysmography, 3 on laser speckle imaging, 3 on ultrasound Doppler flowmetry, 1 on magnetic resonance imaging, 1 on transillumination, 1 additional study on photoplethysmography, and 2 studies on thermometry (Fig. 2).

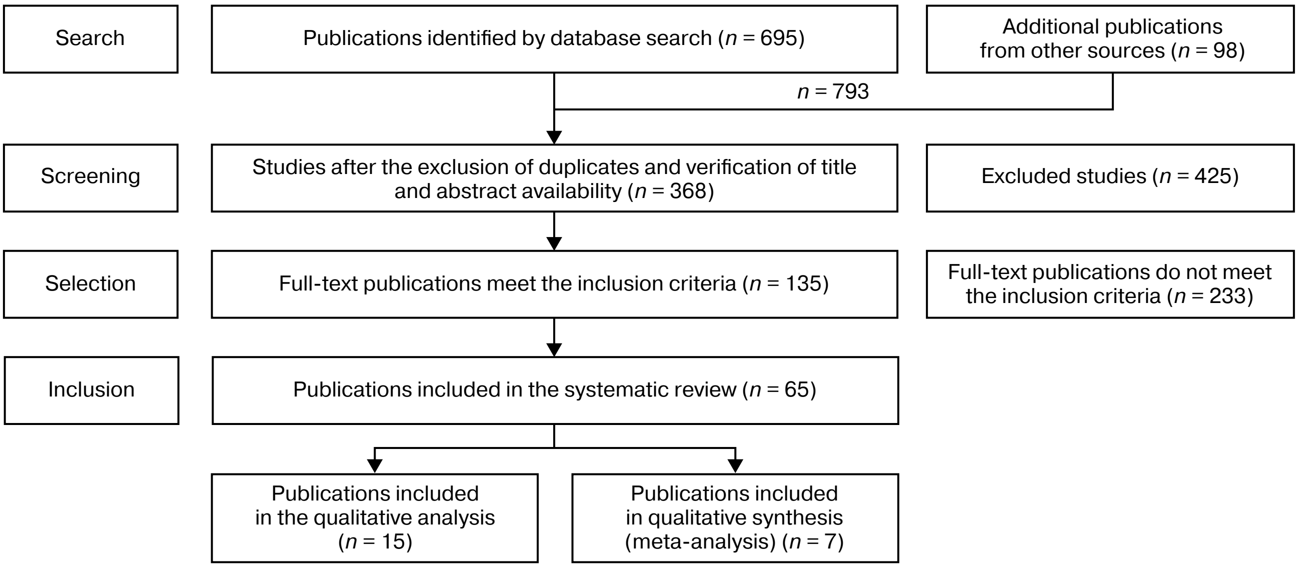


Fig. 1. Block diagram of the study selection process for this systematic review (protocol PRISMA)

Рис. 1. Блок-схема процесса отбора исследований для данного систематического обзора (протокол PRISMA)

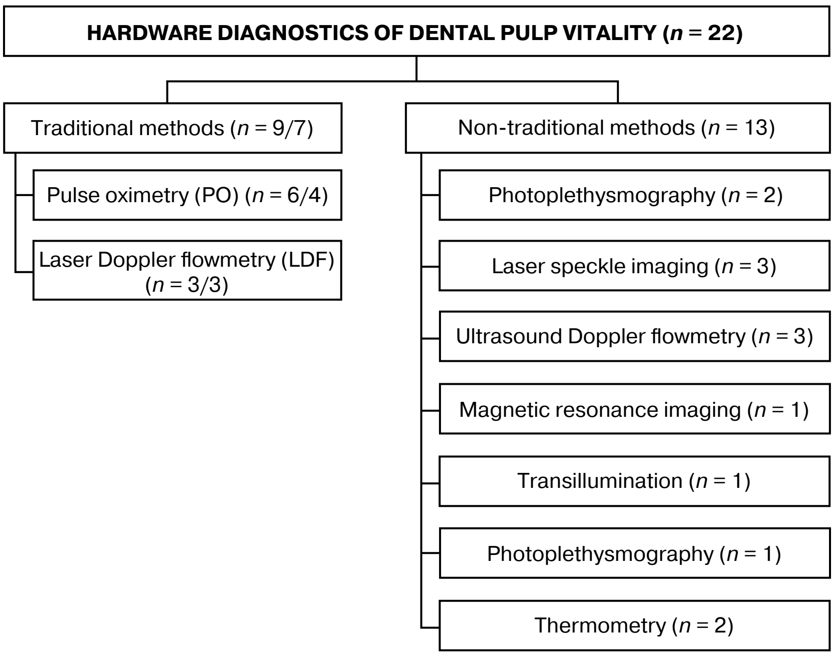


Fig. 2. Hardware methods for determining pulp vitality included in the review

Рис. 2. Вошедшие в обзор аппаратные методы определения витальности пульпы

Only traditional device-based methods – pulse oximetry and laser Doppler flowmetry (7 studies) – were included in the quantitative analysis, as non-traditional methods are still under development, require further research, and have not yet been integrated into clinical practice.

The patent search identified 424 patents related to the field of interest. Patents were excluded if they involved pulp sensitivity testing methods (thermal or electric), lacked relevance, or had no diagnostic value. After screening, 35 records were selected, of which 4 patents were included in the present study.

Tooth Pulp Structure

The average pulp volume in an adult human tooth is approximately 0.02 cm^3. Histologically, four distinct cellular zones can be identified within the pulp: the odontoblastic zone, the cell-free zone, the cell-rich zone, The odontoblastic zone consists of a pseudostratified layer of highly differentiated odontoblasts responsible for dentin production. The cell-free zone is a subodontoblastic area in the coronal pulp, approximately 40 µm thick. This zone contains branching cytoplasmic processes of cells located in the adjacent cell-rich zone. It also forms the main part of the subodontoblastic capillary plexus and contains terminal branches of both sensory and autonomic nerve fibers. The cell-rich zone houses fibroblasts and undifferentiated mesenchymal cells. The undifferentiated cells exhibit spindle-shaped nuclei; in the coronal pulp, their cytoplasmic processes are oriented perpendicularly to the dentin, whereas in the radicular pulp, the orientation is parallel to the dentin [28].

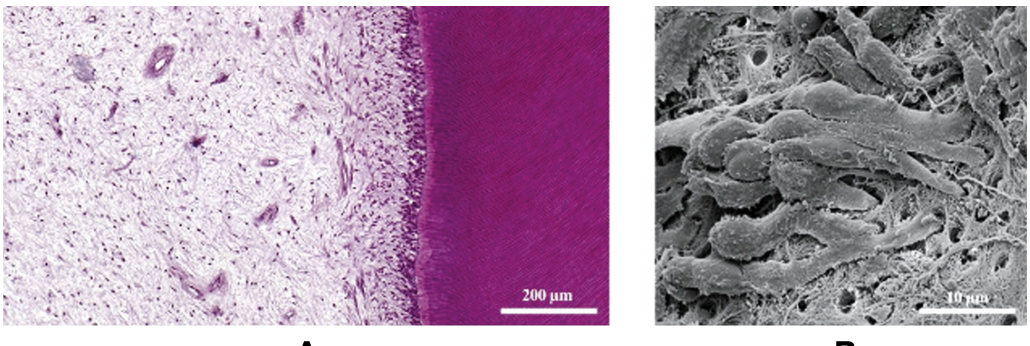
Functionally and developmentally, the pulp and dentin form a closely integrated unit known as the pulp-dentin complex, which originates from the cranial neural crest. Odontoblasts form a continuous layer at the periphery of the pulp, adjacent to the dentin (Fig. 3).

Due to their anatomical location, these cells are the first to encounter harmful stimuli and play a key role in their detection and mediation of tissue responses [29]. Odontoblasts produce the collagenous framework (predentin), which subsequently undergoes mineralization to form dentin. A thin cellular process from each odontoblast remains embedded within the mineralized matrix, giving rise to the characteristic tubular structure of dentin [28].

The processes of pulp odontoblasts terminate at the dentinoenamel or cementodentinal junctions. Evidence suggests that odontoblast processes do not extend deeper than 0.5 mm into the dentin [30]. The orientation of dentinal tubules is believed to be important for interpreting pulp test responses in various regions of the tooth crown. Dentinal tubules typically follow an almost straight path from the incisal edge of anterior teeth toward the pulp horn. In multicusped teeth, the course of the tubules is more curved, forming an “S”-shaped configuration. Primarily, the fluid within the dentinal tubules enables the conduction of electrical impulses from the testing electrode to the pulp. A shorter distance between the electrode and the pulp corresponds to lower electrical resistance [29; 30].

The core of the dental pulp, rich in fibroblasts, collagen, hyaluronan, proteoglycans, and water, resembles mesenchymal and gelatinous connective tissue [29]. Dental pulp tissue is highly innervated and extensively vascularized [28; 30]. Entering the tooth from the alveolar bone through the apical foramen, the network of blood vessels and nerve fibers permeates the entire pulp. The vascular architecture of the pulp is hierarchically organized: arterioles extend toward the center and branch out to form a capillary network at the periphery of the pulp. This network provides odontoblasts with a continuous supply of nutrients. Blood flow is greater in the peripheral pulp than in the central regions and is higher in the coronal pulp compared to the radicular pulp. Capillaries with fenestrated endothelium are predominantly located at the pulp periphery, whereas somatic capillaries are found in the regions of precapillary arterioles and postcapillary venules. Approximately 90% of the pulp’s capillaries are located within the subodontoblastic zone [32].

The dental pulp contains numerous arteriovenous connections (shunts) that regulate blood flow, particularly in the apical region. These shunts also play a crucial role in controlling tissue pressure. The vessels may



A B

Fig. 3. The dental pulp: (*A*) histology of the dentine-pulp complex; (*B*) odontoblast layer depicted by scanning electron microscopy (modified from [29])

Рис. 3. Пульпа зуба: (*А*) гистология комплекса дентин-пульпа; (*В*) слой одонтобластов, визуализация с помощью сканирующей электронной микроскопии (модифицировано из [29]) form arteriovenous anastomoses, venovenous anastomoses, or U-shaped loops, which provide a direct connection between arterioles and venules. When intrapulpal pressure increases during pulp inflammation, these shunting vessels open to reduce the pressure and maintain blood flow [29; 33].

Sensory nerves of the pulp are involved in the perception and transmission of pain impulses. They follow the same path as the blood vessels, extending coronally and peripherally. The highest concentration of neural elements is observed in the region of the pulp horn, which corresponds with heightened pain sensitivity in this area. A progressive decrease in nerve fiber density is noted in the cervical and radicular regions. The pulp tissue exhibits the highest density of unmyelinated C fibers, which innervate the pulp core. Myelinated A fibers, which innervate the periphery of the pulp tissue (extending into the dentinal tubules), are subdivided based on their diameter and conduction velocity into A-beta (Aβ) and A-delta (Aδ) fibers [29; 31]. Approximately 90% of these are thinly myelinated A-delta fibers, whereas A-beta fibers are less prevalent. Compared to C fibers, A-delta fibers have a lower electrical threshold and respond more rapidly to stimuli [31].

Nerve fibers extensively branch throughout the pulp chamber, forming the *Raschkow's plexus* beneath the odontoblastic layer [29]. These fibers are primarily of trigeminal origin and include both myelinated (10–30%) and unmyelinated C fibers (70–90%). As sensory nerve fibers, they play a critical role in detecting stimuli such as temperature changes, pressure, and tissue injury [34]. Myelinated A fibers are concentrated in the peripheral region of the pulp, particularly near the dentin and in the subodontoblastic layer, and are responsible for transmitting sharp, well-localized, stimulus-dependent sensations. In contrast, unmyelinated C fibers are located in the central region of the pulp tissue and are associated with the transmission of diffuse, dull, and stimulus-resistant pain sensations [35].

Traditional Approaches to Assessing Dental Pulp Vitality

Devices used to assess pulp vitality determine the blood supply to the tissue and, as such, may be considered more accurate and reliable non-invasive tools for routine use in dental practice. These include, primarily, pulse oximetry, dual-wavelength spectrophotometry, and laser Doppler flowmetry. Dual-wavelength spectrophotometry has been investigated only under laboratory conditions, where it detects hemoglobin in the blood but does not measure actual blood flow [12].

In this context, we conducted a comparative analysis of the two most widely used methods in dentistry–pulse oximetry (PO) and laser Doppler flowmetry (LDF). These techniques are currently the most well-developed and recommended for assessing pulp vitality. The publications selected for analysis and the corresponding study results are summarized in Table 1.

The devices and systems used in the studies for assessing pulp vitality are presented in Table 2.

Pulse oximetry (PO) has emerged as an alternative method for evaluating the vascular response in dental pulp. It is non-invasive and atraumatic, which enhances its value in dental practice. Pulse oximetry is a physiometric, objective technique based on spectrophotometry and photoplethysmography that measures the oxygen saturation (SpO_2%) of the pulp. One arm of the device sensor consists of light-emitting diodes (LEDs) that emit red light (640 nm) and infrared light (900 nm).

Table 1. Studies selected for analysis

Таблица 1. Исследования отобранные для анализа

Publication	Teeth	Age, years	Sensitivity / specificity*	Conclusions
Pulse Oximetry				
Janani et al., 2020 [36]	79	18–56	100 / 100	Higher diagnostic accuracy compared to sensitivity tests
Janani et al., 2020 [15]	37	18–50		
Molassadolah et al., 2022 [37]	280	7–13	95 / 100	
Farughi et al., 2021 [38]	20	N.R.	100 / 54.5	Among pulp vitality tests, it demonstrates the highest performance, but its results are lower compared to sensitivity-based tests
TOTAL	416	7–56	98.7 / 88.6	Advantages over other pulp vitality tests
Laser Doppler flowmetry and visualization				
Ghouth et al., 2019 [39]	148	8–16	53 / 33	It was not possible to differentiate between teeth with vital and non-vital pulp
Lee et al., 2023 [40]	84	N.R.	100 / 94	It holds promise for timely and accurate assessment of pulp vitality in cases of dental trauma
Yang et al., 2023 [41]	2244	7–12	36.99 / 99.88	
TOTAL	2711	7–16	63.33 / 75.62	The results are contradictory

Note: PO – pulse oximetry; N.R. – not reported; * sensitivity – the ability of a test to detect a disease in patients with the disease; specificity – the ability of a test to detect the absence of a disease.

Примечание: N.R. – не сообщается; * чувствительность – способность теста обнаруживать заболевание у пациентов, имеющих заболевание; специфичность – способность теста обнаруживать отсутствие заболевания.

Light is transmitted through the pulp's arterial vasculature and received by a photodetector on the opposite side. Oxygenated and deoxygenated hemoglobin within the vascular system absorb the emitted red and infrared light differently. Pulsatile changes in blood flow produce variations in light absorption, which are used to determine the oxygen saturation of arterial blood. Healthy dental pulp exhibits a high oxygen saturation level, whereas progression from a healthy to an inflamed state is associated with a decrease in oxygen levels [12; 42]. Studies published during the reviewed period have demonstrated promising results supporting the use of pulse oximetry as a diagnostic tool for assessing pulp vitality [12; 16; 42; 43].

We reviewed six studies involving the use of pulse oximetry to assess pulp vitality during the observation period, of which four were selected for qualitative synthesis [15; 36–38] (Table 1).

Janani et al. evaluated the diagnostic accuracy of a dental pulse oximeter equipped with a customized sensor holder. The highest diagnostic accuracy was achieved with the pulse oximeter (100%), followed by the cold test (66%), heat test (49%), and electric pulp test (45%). The study concluded that the pulse oximeter with a custom-designed sensor holder demonstrated superior diagnostic accuracy compared to conventional pulp sensitivity tests [15, 36].

In a study by F. Molaasadolah et al., pulse oximetry was confirmed to have higher sensitivity (95%), specificity (100%), and better overall accuracy (98.7–100%) than both the cold test and electric pulp test in evaluating pulp vitality [37].

According to findings by S. Mishra et al., pulse oximetry was identified as the most accurate test for diagnosing both normal and inflamed pulp conditions [44]. However, in a study by A. Farughi et al. involving premolars requiring root canal treatment, although pulse oximetry demonstrated high sensitivity, it showed lower specificity and accuracy compared to conventional pulp sensitivity tests [38].

Of particular interest is the use of pulse oximetry in pediatric patients, where it has been shown to be an effective test for assessing pulp vitality in both immature and mature permanent incisors [12; 45]. A strong correlation between pulse oximetry readings and traditional pulp sensitivity tests was also established [45].

Given the lack of pulse oximeters specifically designed for dental applications, the feasibility of using devices intended for neonatal intensive care units has been justified. A significant difference in pulp oxygenation levels was observed between teeth with various pulp pathologies (reversible pulpitis, irreversible pulpitis, and pulp necrosis). It was found that pulp diseases lead to a reduction in oxygen saturation of the vascular network, thereby affecting pulp vitality. The authors emphasized that pulse oximetry is particularly well-suited for determining SpO_2% in children, as it combines high diagnostic efficiency with a non-invasive and chairside-friendly approach suitable for routine dental examinations [12].

Thus, the oxygen saturation values obtained from vital teeth support the potential of pulse oximetry as a diagnostic tool for identifying pulp pathology. All reviewed studies confirmed the high diagnostic value of pulse oximetry in assessing pulp vitality. However, studies aimed at establishing reference values for pulp oxygen saturation remain limited. According to S.K. Betal, the mean SpO_2 values in healthy primary molars were 95.4 ± 0.7%, in cases of reversible pulpitis – 91.5 ± 1.35%, irreversible pulpitis – 89.3 ± 1.26%, and pulp necrosis – 86.9 ± 1.92% [12; 45].

Table 2. Devices / systems used in studies to assess pulp vitality

Таблица 2. Устройства / системы, используемые в исследованиях для оценки витальности пульпы

System / device (publication)	Purpose / Aim
Pulse Oximetry	
Dental pulse oximeter (Nellcor N-600, Healthcare Group LP, Pleasanton, California) [15]	Measuring blood oxygen saturation (SaO_2)
The Alborz B5 pulse oximeter (Masimo SET/SAADAT, Iran) and the FMT-RAF-MSM-L sensor (Metko Ltd., Istanbul, Turkey), modified for dental application, were used [37]	
A custom-made pulse oximeter specifically designed for dental use by modifying a commercial finger pulse oximeter (PO) by an electrical engineer [44]	
A pulse oximeter used in a neonatal intensive care unit (NICU) [12]	
A pediatric probe of the pulse oximeter (CMS60D, Contec Medical Systems Co. Ltd., China), adapted to the tooth surface [45]	
Laser Doppler flowmetry and visualization	
A dual-channel Moor VMS-LDF 2 device (Moor Instruments, Axminster, UK) was used, with a maximum output power of 2.5 mW, a wavelength of 785 ± 10 nm, and a probe frequency filter of 15 kHz. Two probes with a diameter of 1.5 mm were employed, each containing two optical fibers with a diameter of 200 µm and an inter-fiber distance of 500 µm [39]	Pulp blood flow
The laser Doppler model MoorLDI-2λ (Micro Star Instruments Co. Ltd., Taipei, Taiwan) was used, featuring an infrared wavelength of 830 nm, a scanning frequency bandwidth of 20 Hz, and a scanning range of 6.6 × 5.5 cm [40]	
LDF device (Perimed PF 5001, Perimed AB, Stockholm, Sweden) with an LDF probe (Perimed DP 416, diameter 1.6 mm, 785 nm; Perimed AB, Stockholm, Sweden) [41]	

The studies included in the meta-analysis (416 teeth) reported an overall low risk of bias. The pooled sensitivity ranged from 95% to 100% (with an average of 98.7%), and specificity ranged from 54.5% to 100% (with an average of 88.6%), suggesting that pulse oximetry has strong diagnostic accuracy, particularly in pediatric populations. Nonetheless, limitations in the clinical application of pulse oximetry for pulp vitality assessment are primarily related to the lack of commercially available dental-specific devices on the market.

In studies evaluating the accuracy of pulse oximetry (PO), custom-made dental probes were used to maintain a consistent optical path length between the light emitted by the LED and the light received by the photoreceptor sensor, thereby ensuring accurate measurements [36; 46].

Laser Doppler flowmetry (LDF) utilizes Doppler-shifted light as a carrier of information. This optical method measures both the quantity and velocity of particles transported by a fluid flow and is currently regarded as an accurate, non-invasive, reproducible, and reliable technique for assessing blood flow in microvascular systems. It employs a diode that projects an infrared light beam through the crown and into the pulp chamber [42]. In recent years, laser Doppler flowmetry has been successfully introduced into dentistry for the measurement of pulpal blood flow [47–51].

The original method employed a helium-neon (He-Ne) laser emitting at a wavelength of 632.8 nm, which underwent frequency shifts upon scattering by moving erythrocytes, in accordance with the Doppler principle. Other wavelengths of semiconductor lasers were also used, including 780 nm and the range of 780–820 nm [48; 49]. In 1991, Pettersson and Oberg utilized LDF to assess pulp vitality in both intact and traumatized teeth. They employed an infrared laser diode with a longer wavelength, which provided greater tissue penetration compared to the He-Ne wavelength. Sasano et al. designed, developed, and tested a transmitted light laser flowmeter that employed a high-powered laser beam to monitor pulp blood flow, as opposed to conventional devices using backscattered light. In 2007, Konno et al. modified the device and demonstrated that a higher-power transmitted light flowmeter (5 mW versus 2 mW) was more effective than the standard backscattered light model in evaluating changes in pulp blood flow during molar intrusion in an animal model [49].

It has been shown that laser light can penetrate densely up to a depth of 4 mm and less densely up to 13 mm. This indicates that, even with proper isolation, contamination by non-pulpal artifact signals – commonly referred to as “noise” – cannot be entirely eliminated, and thus false results remain a possibility [47]. However, a study involving 28 discolored teeth demonstrated that the presence of blood pigments did not interfere with laser Doppler flowmetry measurements [47].

A. Belcheva et al. confirmed that LDF can detect changes in pulpal blood flow (PBF) during the “ischemic phase,” in contrast to traditional pulp sensitivity tests [51]. H.J.J. Roeykens et al. reported the successful application of laser Doppler flowmetry for monitoring arterial blood flow within the dental pulp [52]. A cohort study involving over 394 selected teeth demonstrated that LDF values were highly reliable in differentiating between the “vitality status” of traumatized and non-traumatized teeth [52].

The meta-analysis of studies on the application of LDF in dentistry during the review period included only three studies—two using laser Doppler flowmetry and one employing laser Doppler imaging for pulp vitality assessment (Table 1). This limited inclusion was due to the lack of data on sensitivity and specificity in other publications.

In a cross-sectional cohort study assessing the vitality of permanent anterior teeth in children, a dual-channel Moor VMS-LDF 2 device (Moor Instruments, Axminster, UK) was used. It had a maximum output power of 2.5 mW, a wavelength of 785 ± 10 nm, and a probe frequency filter of 15 kHz. Two probes were used, each 1.5 mm in diameter, equipped with two 200 µm optical fibers spaced 500 µm apart. A stable 30-second LDF signal was recorded. The participants (74 children) had either a maxillary central or lateral incisor with completed root canal treatment or pulp removal, along with a contralateral tooth with a vital pulp. However, laser Doppler flowmetry failed to distinguish between vital and non-vital pulps in these cases. The results indicated a high likelihood of false readings, and further research is needed to validate the clinical applicability of LDF for pulp blood flow assessment, particularly in pediatric patients [39].

Subsequently, two studies conducted in 2023 yielded more favorable results [40; 41]. Both investigations focused on dental trauma. K. Yang et al. examined pulp vitality and pulpal blood flow (PBF) in permanent maxillary incisors of healthy children using LDF. The researchers established a clinical reference range and calculated concordance rates for pulp vitality using PBF as an indicator.

A clinical reference range for PBF values in healthy permanent anterior teeth was determined as follows: overall, the reference range for healthy maxillary permanent incisors in children was defined between 7 and 14 PU. Tooth 11: 6.016–11.900 perfusion units (PU); Tooth 12: 6.677–14.129 PU; Tooth 21: 6.043–11.899 PU; Tooth 22: 6.668–14.174 PU

The clinical concordance rate of LDF in diagnosing pulp vitality was 90.42%. While LDF demonstrated high specificity, it was associated with low sensitivity [41].

In 2023, the first application of laser Doppler imaging (LDI) as a diagnostic tool for traumatic pulp necrosis was reported. The device used was the MoorLDI-2λ laser Doppler tomograph (Micro Star Instruments Co. Ltd., Taipei, Taiwan), featuring an infrared wavelength of 830 nm, a scan frequency bandwidth of 20 Hz, and a scanning range of 6.6 cm × 5.5 cm. The system measured microvascular blood flow and concentration within 1 mm from the surface. A single image scan enabled large-scale simultaneous imaging of both maxillary and mandibular anterior teeth.

The optimal cut-off value for the entire laser Doppler tomograph was determined to be 31.55. However, during the recovery phase, the tooth blood flow values frequently fell between those of necrotic and healthy pulps. The closer the value was to the cut-off point, the more difficult it became to establish a definitive diagnosis. Despite this, the method demonstrated high sensitivity and specificity [40].

The overall findings of the studies included in this review demonstrated that pulp vitality tests using pulse oximetry (PO) and laser Doppler flowmetry (LDF) are more reliable methods for determining the actual condition of the pulp in endodontics compared to traditional pulp sensitivity tests [36; 46]. An exception was the study by Ghouth et al., which reported that LDF was unable to distinguish between teeth with vital and nonvital pulp, indicating a high probability of false-positive or false-negative results [39].

Electric Pulp Testing (EPT). Due to its high inorganic content, healthy enamel acts as an electrical insulator. Demineralization of enamel increases surface porosity, allowing saliva to fill these microspaces and create conductive pathways for electric current. The degree of demineralization is directly proportional to the electrical conductivity. Electrical resistance serves as a measure of conductivity through these microscopic spaces or pores.

A device known as the *Van Guard electronic caries detector* was developed to measure the tooth's electrical conductivity. Conductivity is numerically expressed on a scale from 0 to 9, indicating progression from a sound tooth to increasing levels of demineralization. A modified version of this device – the *Electronic Caries Monitor* – detects caries at a specific point on the tooth and can also scan the entire occlusal surface by applying a conductive medium prior to probe placement.

Measurements of electrical resistance have been performed using devices such as the ECM (Lode Diagnostics, Groningen, Netherlands – now discontinued) and the AC impedance spectroscopy technique (ACIST, CarieScan Pro, CarieScan, Charlotte, NC, USA) [53].

In Russia, *Geosoft Dent* devices are widely used by dentists. These instruments function by delivering gradually increasing low-intensity electrical impulses through dental tissues–enamel, dentin, dentinal tubules, and nerve endings. The clinician registers the pulp's response to stimulation. Based on the current intensity at which the pulp responds, the practitioner assesses its vitality. In the presence of pathological conditions, pulp nerve receptors exhibit reduced excitability, resulting in decreased patient sensitivity to electrical stimulation.

CONCLUSION

Accurate diagnosis of the dental pulp and adjacent periapical tissues is essential for making well-informed therapeutic decisions. However, diagnosing pulp status remains a complex task, as conventional pulp sensitivity tests rely on neural stimulation, making them dependent on the subjective response of the patient and the clinician's interpretation. These methods do not assess the true indicator of pulp vitality – its blood supply. Sensitivity tests primarily evaluate the presence of neural activity, which can be temporarily impaired, leading to false-positive or false-negative outcomes. Nevertheless, such methods and electric pulp testing devices remain widely used in clinical practice.

The measurement of pulpal blood flow and oxygenation may provide an objective approach to determining pulp vitality. Pulse oximetry (PO) and laser Doppler flowmetry (LDF) have garnered increasing interest from both researchers and practicing clinicians. While these methods are still under investigation, they have already been recognized for offering reproducible and objective assessments of pulp viability. However, technical limitations present challenges in interpreting test accuracy. For example, PO requires custom-fabricated probes, and interference from xenon overhead lights or elevated carbon dioxide levels in the bloodstream may affect deoxygenation readings, resulting in false measurements. In the case of LDF, false-negative results may occur when the laser path is obstructed, falsely indicating the absence of blood flow. Similarly, signal contamination or noise from non-pulpal sources-particularly periodontal tissues–may mimic pulpal blood flow, producing misleading values. Moreover, the LDF procedure currently requires approximately one hour, rendering it impractical for routine dental use unless the measurement time is significantly reduced.

Based on the results of the reviewed international publications from 2019 to 2024, it can be concluded that *pulse oximetry* is currently the most accurate diagnostic tool for assessing pulp vitality. It can be effectively used to evaluate the viability of both immature and mature permanent incisors in children. However, the clinical use of pulse oximetry is limited by the lack of commercially available devices specifically designed for dental applications.

The diagnostic value of *laser Doppler flowmetry* (LDF), by contrast, remains uncertain. Its clinical implementation is constrained by several factors, including lengthy measurement times (recordings typically take around one hour), lack of reproducibility (due to uncontrolled probe movement), and the high cost of the equipment and procedures.

Despite the significant potential of both pulse oximetry and laser Doppler flowmetry, their routine application in dentistry for determining pulp vitality remains limited by technical barriers and a shortage of large-scale clinical studies. In Russia, such investigations are still in the developmental stage.

LIMITATIONS

This review has several limitations. It was not possible to fully eliminate clinical heterogeneity among the included studies. The sample sizes were relatively small, which limited the statistical power of the findings. Analysis by specific tooth types (incisors, canines, premolars, and molars) and dental arches was not performed due to the limited number of included tooth types and the variation in tooth distribution between the maxillary and mandibular arches. Clinical variability related to age and gender models also could not be excluded.

Moreover, the limited number of studies involving laser Doppler flowmetry (LDF) restricted its inclusion in the quantitative synthesis.

It should be noted that pulp vitality tests have technical limitations, such as the need to monitor gingival blood flow, which requires the use of a dental splint and stabilization of the patient's head relative to the probe – procedures that were not included in the methodologies of the reviewed studies. Furthermore, there is a lack of high-quality research on methodological validity, highlighting the need for well-designed in vivo studies to evaluate the diagnostic accuracy of pulp vitality assessment and the sensitivity of electric pulp testing.

Future recommendations include conducting studies with larger sample sizes. Additionally, investigations involving severely curved root canals should be considered, ideally using randomized controlled in vivo study designs.

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