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Review Article

Pulse oximetry as a dental pulp test: A scoping review to identify barriers hindering the use of oximeters in clinical practice

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A R T I C L E I N F O

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A B S T R A C T

Background and Objective: Although medical pulse oximeters are considered effective for endodontic diagnoses, the method remains uncommon in current dental practice. The aim of the present scoping review was to investigate clinical factors that exert a negative impact on the use of pulse oximeters in dental practice.
Methods: This study followed the PRISMA-ScR guidelines and the protocol was prospectively registered in the Open Science Framework (https://doi.org/10.17605/OSF.IO/3GQCE). A comprehensive search of the MEDLINE (via PubMed), Cochrane Library, and Web of Science databases was performed in December 2022 for articles published in English or Spanish. All types of clinical studies were included, except comments, letters to the editor, and abstracts. Two independent investigators analyzed 45 full-text articles. Data extraction included general characteristics, oxygen saturation levels, and limiting factors/barriers to the use of oximeters as pulp testers.
Results: The search of the databases yielded 1,300 records and 38 were included (quantitative data extraction was performed for 35 and three articles were systematic reviews). Publications were highest in number between 2016 and 2017, with an evident reduction occurring after 2021. The oxygen saturation level for sound/vital maxillary anterior teeth was 84.99% (overall mean). The main limiting factors/barriers were i) the difficulty in maintaining the two light-emitting diodes parallel during pulp tests, ii) infrared light diffraction by enamel/dentin/gingiva, and iii) the diversity of patient ages in studies.
Conclusion: This scoping review encountered noteworthy findings associated with the impracticability of using medical pulse oximeters as dental pulp testers. The recent decrease in the frequency of published studies compared to approximately seven years ago may imply a negative trend in the use of the method.

1. Introduction

Pulse oximeters have a considerable value in endodontic diagnoses, as these devices can measure oxygen saturation in the pulp blood supply, which is the strongest determinant of pulp vitality (Gopikrishna et al., 2007). Moreover, tooth sensibility is due to the intactness and health of the vascular supply (Jafarzadeh and Abbott 2010a, 2010b). Thus, a clinical test that determines blood flow (opposed to assessing the responsiveness of pulpal sensory neurons, such as electrical, mechanical, or thermal tests) (Jafarzadeh and Abbott 2010a, 2010b) is considered the ideal pulp diagnostic test. The ability to diagnose unviable vascular tissue in the initial stages of injured teeth would eliminate the need to wait for signs of pulp necrosis and such a finding would be an indication for immediate root canal treatment, further minimizing injury-related sequelae (McCabe and Dummer, 2012, Stella et al., 2015).

When used in medicine, the oximeter is normally attached to the patient's finger, whereas an adapter is recommended for use in dentistry to ensure that the pulse oximeter is correctly positioned by holding the light-emitting diodes (LEDs) parallel to each other and ensuring that the light passes through the crown (Jafarzadeh and Rosenberg, 2009). These two LEDs have different wavelengths [one red (640 nm) and one infrared (940 nm)], operating in cycles of 500 emissions per second. The

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emissions from these light sources are captured by a receiving photodiode and converted into arterial oxygen saturation and pulse rate (Sharma et al., 2019). Higher levels of oxygen saturation in permanent teeth are described for vital pulp (Bruno et al. 2017).

Although oximeters are considered effective for endodontic diagnoses, the method remains uncommon in current dental practice (Mishra et al., 2019). The available literature is composed of primary studies with samples limited to some tooth groups and considerable methodological variability, resulting in gaps in knowledge as well as an absence of protocols and guidelines for the use of pulse oximeters in the field of endodontics. Therefore, the aim of the present scoping review was to answer the following question: 'What clinical factors exert a negative impact on the use of pulse oximeters in dental practice and the proper determination of pulp status?'

2. Methods

This scoping review was conducted in December 2022. The protocol followed the 'Preferred Reporting Items for Systematic Reviews and Meta-Analysis Protocols' (PRISMA for Scoping Reviews) (Moher et al., 2009), the 'Guidance for Conducting Systematic Scoping Reviews' (Peters et al., 2015), and the 'PRISMA Extension for Scoping Reviews (PRISMA-ScR): checklist and explanation' (Tricco et al., 2018). The protocol was prospectively registered in the Open Science Framework under https://doi.org/10.17605/OSF.IO/3GQCE and it is available at https://osf.io/3gqce/.

2.1. Eligibility criteria

The model used for eligibility was guided by the Population, Concept, and Context method, as recommended by the JBI Manual for Evidence Synthesis (Aromataris and Munn, 2020). Population: '*patients teeth*'; Concept: '*diagnosis of tooth pulp status using pulse oximeters to detect oxygen saturation levels*'; Context: '*clinical factors limiting the use of pulse oximetry in endodontics*'. Clinical studies involving humans and published in English or Spanish were included. Systematic reviews were included to support the discussion but the data from these reviews were not incorporated in the quantitative analysis (see Flowchart/Fig. 1). Articles that did not provide a full text, abstracts, conference summaries, comments, and letters to the editor were excluded.

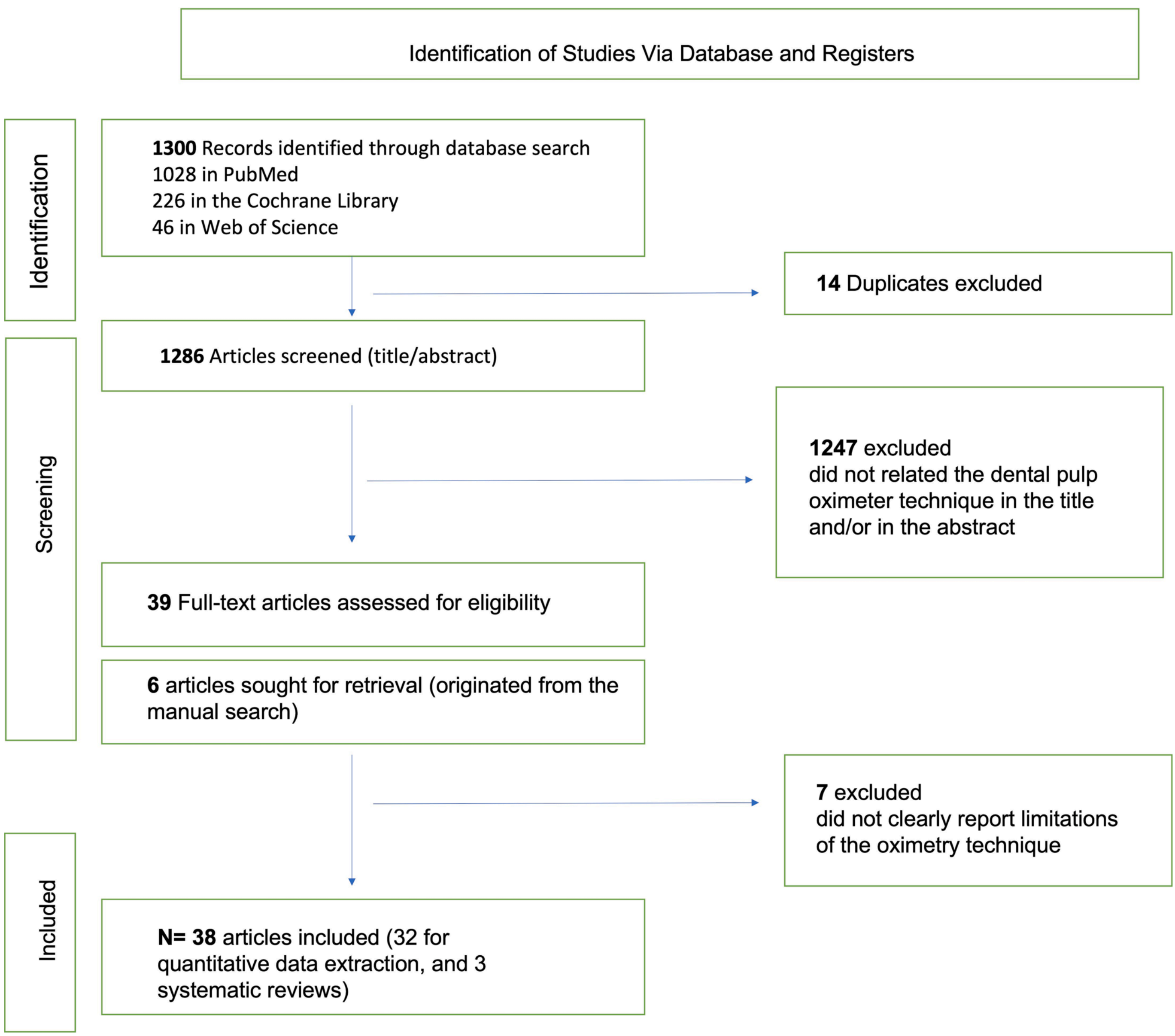

Fig. 1. Flow diagram of study selection.

2.2. Search strategy & article selection

An initial search was conducted of some scientific articles addressing the use of pulse oximeters for the determination of pulp status to select appropriate descriptors/keywords. Subsequently, the Medline (PubMed), Cochrane Library, and Web of Science databases were searched to identify potentially relevant articles. Descriptors using Boolean operators (AND, OR) followed the search criteria of each database: 1) PubMed – ((((((Pulp Test, Dental[MeSH Terms]) OR (Test, Dental Pulp[MeSH Terms])) OR (Oximetry, Pulse[MeSH Terms])) OR (Oximetries, Pulse[MeSH Terms])) OR (Saturation, Oxygen[MeSH Terms])) OR (Blood Oxygen Levels[MeSH Terms])) AND (Oral Diagnosis [MeSH Terms]); 2) Cochrane Library - "pulse oximeter" in Keyword OR "pulse oximetry" in Keyword AND "pulp test" in Keyword; and 3) Web of Science - Pulp Test, Dental AND Oximetry, Pulse (All Fields). We also conducted a hand search of the references cited in the articles included in the present scoping review. The final search results were exported to the EndNote software (EndNoteX9.3.1, Clarivate Analytics Philadelphia, USA) and duplicates were removed.

Two independent reviewers (RHK and MRC) sequentially screened the titles and abstracts of the articles retrieved from the searches and selected articles for full-text analysis based on the eligibility criteria. In cases of a divergence of opinion between the reviewers even after a consensus meeting, a third experienced reviewer (SAMJ) was consulted to make the final judgment.

2.3. Data extraction

A data mapping form was jointly developed by the reviewers to determine what variables to extract. The two reviewers participated in a calibration session using a random sample of 10 % of the selected articles. In addition to checking intra- and inter-reviewer reproducibility, the extracted data were discussed in order to adapt the data mapping form.

The following data were extracted: title, year of publication, name of journal, corresponding author/country in which the study was conducted, objectives, study design, and participants' ages and sex. Methodological characteristics were also extracted, such as the calculation of the sample size, the existence of control and experimental groups, tooth number, number of operators/evaluators, oximeter brand/model, oximeter probe type, measurement technique, confirmatory test for pulp vitality (e.g., cold test), pulse oximeter results, and limiting factors/barriers to the use of the oximeter method reported in the studies.

2.4. Synthesis

The descriptive synthesis of the results focused on the following two questions: i) What are the general characteristics of the included studies, such as study design, sample size, and oxygen saturation values? ii) What clinical factors limit/complicate the use of pulse oximetry in endodontics.

3. Results

3.1. General characteristics of studies included

The searches of the databases yielded 1,300 records (1,028 in PubMed, 226 in the Cochrane Library, and 46 in Web of Science). After the removal of duplicates and the screening of titles/abstracts, 39 articles were submitted to a first round of full-text analysis. Moreover, six articles found through the hand search of references were included and also submitted to the first round of full-text analysis. After a second round of full-text analysis, seven articles were excluded (Birang et al., 2008, Kataoka et al., 2011, Kataoka et al., 2012, Khademi et al., 2021, Khajehahmadi et al., 2013, Liao et al., 2017, Setzer et al., 2012) for not clearly reporting limitations to the use of the oximetry method. Thus, a total of 38 articles were included in the present scoping review (Fig. 1).

The 38 articles (including three systematic reviews that met the inclusion criteria) (Almudever-Garcia et al., 2021, Lima et al., 2019a, 2019b, Mainkar and Kim, 2018) were published between 1991 and 2022. Publications were higher in number between 2016 and 2017, with an evident reduction in publications after 2021. The ranking in descending order of the countries with the largest number of publications was as follows: Brazil (n = 13; 34.21 %); India (n = 11, 28.95 %); Iran (n = 3, 7.90 %); Turkey (n = 2, 5.26 %); United States (n = 2, 5.26 %); South Korea (n = 1, 2.63 %); Peru (n = 1); Finland (n = 1); Lithuania (n = 1); England (n = 1); Spain (n = 1); and Sweden (n = 1). The scientific journal with the largest number of publications was the '*Journal of Endodontics*' (31.6 %).

The characteristics of the studies (country, study design, tooth groups, and oxygen saturation levels) are displayed in Table A1. This table consists of 35 articles, as the systematic reviews were left out to avoid data duplication.

The study designs were observational longitudinal prospective (65.8 %), diagnostic accuracy (18.4 %), randomized clinical trial (n = 3, 7.9 %), and systematic reviews (n = 3, 7.9 %).

The oximetry method was performed by groups of teeth, with maxillary anterior teeth the most widely investigated. Oxygen saturation levels for maxillary anterior teeth considered sound/vital were 84.99 % (overall mean) and 84.30 % (overall median) (Bargrizan et al., 2016, Calil et al., 2008, Gopi Krishna et al., 2006, Radhakrishnan et al. 2022, Sadique et al., 2014, Solda et al., 2018, Stella et al., 2015, Schnettler and Wallace, 1991). When studies grouped sound/vital maxillary and mandibular anterior teeth the values were 81.09 % (overall mean) and 93.60 % (overall median) (Anusha et al., 2017, Neves Henriques et al., 2022, Kahan et al., 1996, Kataoka et al., 2016). Oxygen saturation for sound/vital molars was 84.93 % (overall mean) (Lima et al., 2019a, 2019b, Radhakrishnan et al., 2002).

When studies justified the sample size and described the calculation (Anusha et al., 2017, Caldeira et al., 2016, Estrela et al., 2017a, Giovanella et al., 2014, Lima et al., 2019a, 2019b, Neves Henriques et al., 2022, Oikarinen et al., 1996, Solda et al., 2018, Stella et al., 2015), the sample size was 104 teeth/study (overall mean). When studies did not describe sample size calculation, 55 teeth/study were included (overall mean) (Bargrizan et al., 2016, Calil et al., 2008, Dastmalchi et al., 2012, Farughi et al., 2021, Gopi Krishna et al., 2006, Gopikrishna et al., 2007, Grabliauskienė et al., 2021, Janani et al., 2020, Kahan et al., 1996, Karayilmaz and Kirzioğlu 2011a, Karayilmaz and Kirzioğlu 2011b, Kataoka et al., 2016, Kong et al., 2016, Mishra et al., 2019, Oikarinen et al., 1996, Pozzobon et al., 2017, Radhakrishnan et al., 2002, Sadique et al., 2014, Setzer et al., 2012, Schnettler and Wallace, 1991, Sharma et al., 2019, Shetty et al., 2016, Souza et al., 2017).

3.2. Results of individual sources of evidence

Limiting factors/barriers to the use of oximeters in clinical practice reported in the studies are displayed in Table A2. A summary of these factors is given below.

1) Difficulty in maintaining the two light diodes parallel: Inaccurate measurements occurred when the LED sensor and detector diodes were not parallel (Kong et al., 2016, Sharma et al., 2019) because the light emitted by the LED sensor was received in smaller quantities by the detector. The clinical differences in the external morphology of different teeth invalidate the use of a single/universal holder with diodes attached to the tooth surface (Anusha et al., 2017, Lima et al., 2019a, 2019b, Mishra et al., 2019). One of the oldest studies included in this review (Kahan et al., 1996) tested a customized commercial probe to attach the pulse oximeter to teeth and found that the oximeter/probe assembly was disappointing and had no clinical value. The authors reported an inaccurate mean of 39.61 % oxygen saturation for sound maxillary and mandibular incisors and

Table A1
General characteristics (authors/year, country of origin, study design, teeth groups, oxygen saturation levels) of the articles which underwent quantitative analysis ($n = 35$). Systematic reviews ($n = 3$) were not included in this table.

Authors (year)	Country of origin	Study design	Teeth groups	Oxygen saturation levels (%)
Kong et al. (2016)	South Korea	Longitudinal	Maxillary Incisors and Canines	>96%
Farughi et al. (2021)	Iran	Longitudinal	Maxillary Incisors and Canines	>86%
Krishna et al. (2006)	India	Diagnostic Accuracy	Maxillary Incisors and Canines	Mean: 79%
Gopikrishna et al. (2007)	India	Longitudinal	Maxillary Incisors and Canines	75 to 85%
Karayilmaz and Kirzioğlu (2011a, 2011b)	Turkey	Longitudinal	Maxillary Incisors and Canines	81 to 93%
Oikarinen et al. (1996)	Finland	Longitudinal	Maxillary Incisors and Canines	Oxygen saturation not reported in percentage
Calil et al. (2008)	Brazil	Diagnostic Accuracy	Maxillary Incisors and Canines	90.99%
Bargrizan et al. (2016)	Iran	Diagnostic Accuracy	Maxillary Incisors and Canines	Immature permanent teeth: 86.71%; Mature permanent teeth: 83.64%
Schnettler and Wallace (1991)	United States	Longitudinal	Maxillary Incisors and Canines	94%
Solda et al. (2018)	Brazil	Diagnostic Accuracy	Maxillary Incisors and Canines	85.10%
Sadique et al. (2014)	India	Longitudinal	Maxillary Incisors and Canines	84.96%
Stella et al. (2015)	Brazil	Longitudinal	Maxillary Incisors and Canines	81.25%
Radhakrishnan et al. (2002)	India	Longitudinal	Maxillary Incisors and Canines	81%
Estrela et al. (2017a, 2017b)	Brazil	Longitudinal	Premolars	86.20%
Dastmalchi et al. (2012)	Iran	Longitudinal	Premolars	86% to 100%
Lima et al. (2019a, 2019b)	Brazil	Longitudinal	Molars	84.76%
Estrela et al. (2017a, 2017b)	Brazil	Longitudinal	Molars	85.09%
Sharma et al. (2019)	India	Longitudinal	Permanent teeth	>85%
Shahi et al. (2015)	India	Longitudinal	Deciduous teeth	Oxygen saturation not reported in percentage
De La Sotta-Rubio and Gonzáles-Mendoza (2014)	Peru	Longitudinal	Deciduous teeth	Reversible pulpitis: 85.3%; Irreversible pulpitis: 83.2%; Pulp necrosis: 85%
Karayilmaz and Kirzioğlu (2011a, 2011b)	Turkey	Longitudinal	Deciduous teeth	84.14%
Anusha et al. (2017)	India	Diagnostic Accuracy	Maxillary and Mandibular Incisors and Canines	Reversible pulpitis: 85.45%; Irreversible pulpitis: 81.6%; Pulp necrosis; 70.7%; Control/ healthy teeth: 94.6%
Kahan et al. (1996)	England	Longitudinal	Maxillary and Mandibular Incisors and Canines	39.61%
Neves Henriques et al. (2022)	Brazil	Longitudinal	Maxillary and Mandibular Incisors and Canines	97.55%
Kataoka et al. (2016)	Brazil	Diagnostic Accuracy	Maxillary and Mandibular Incisors and Canines	Radiotherapy patients: 92.7%; Control/no treatment patients: 92.6%
Caldeira et al. (2016)	Brazil	Longitudinal	Maxillary Incisors and Canines & Premolars	93%
Gopikrishna et al. (2007)	India	Randomized Clinical Trial	Maxillary and Mandibular Incisors and Canines & Premolars	75 to 85%
Grabliauskienė et al. (2021)	Lithuania	Randomized Clinical Trial	Maxillary and Mandibular Incisors and Canines & Premolars	93.17%
Souza et al. (2017)	Brazil	Longitudinal	Maxillary and Mandibular Incisors and Canines & Premolars & Molars	Healthy patients: 88.3%; Sickle-cell anemia patients: 85.5%
Mishra et al. (2019)	India	Longitudinal	Deciduous teeth & Permanent teeth	Irreversible pulpitis: 83.54%; Control/ healthy teeth: 84.73%
	India	Longitudinal	Maxillary Incisors and Canines	75 to 85%
Shetty et al. (2016)	India	Randomized Clinical Trial	Maxillary Incisors and Canines	
Giovanella et al. (2014)	Brazil	Diagnostic Accuracy	Maxillary Incisors and Canines	
Janani et al. (2020)	India	Longitudinal	Maxillary Incisors and Canines & Premolars	
Setzer et al. (2012)	United States	Longitudinal	Premolars & Molars	Not reported

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Table A1 (*continued*)

Authors (year)	Country of origin	Study design	Teeth groups	Oxygen saturation levels (%)
Pozzobon et al. (2017)	Brazil	Longitudinal	Deciduous teeth & Permanent teeth	

attributed this to the lack of parallelism between the two light diodes. Movements of the patient's head and swallowing reflexes were other reasons for the poor placement of the diodes (Caldeira et al., 2016, Calil et al., 2008, Estrela et al., 2017a, Neves Henriques et al., 2022, Stella et al., 2015). Researchers have attempted to create devices to hold the pulse oximeter around teeth. Grabliauskienė et al. (2021) recently published the results of the development of a 'universal' 3D-printed probe holder for measuring oxygen saturation in sound teeth. The probe was developed based on the principle of sliding tweezers in order to adapt the sensor to different dental anatomies. The authors found a 93.17 % mean oxygen saturation level irrespective of the tooth group in 26-year-old patients (on average) and concluded that their 3D printed probe had potential to be used in clinical practice. Infrared light diffraction: The diffraction and scattering of infrared light by prisms of enamel, dentin (Anusha et al., 2017, Bargrizan et al., 2016, Estrela et al., 2017a, Estrela et al., 2017b, Giovanella et al., 2014, Gopi Krishna et al., 2006, Gopikrishna et al., 2007, Grabliauskienė et al., 2021, Janani et al., 2020, Karayilmaz and Kirzioğlu 2011a, Neves Henriques et al., 2022, Oikarinen et al., 1996, Radhakrishnan et al., 2002, Sadique et al., 2014, Sharma et al., 2019, Souza et al., 2017, Stella et al., 2015), and gingival tissue (Gopi Krishna et al., 2006, Janani et al., 2020, Kahan et al., 1996, Radhakrishnan et al., 2002) was one of the most reported challenges in the articles. Pulp is surrounded by hard tissues that can have different thicknesses and morphologies. Enamel and dentin act as obstacles to the light, dissipating it through enamel prisms and dentinal tubules (Bruno et al., 2014). This same dissipation effect can occur through gingival tissue (Anusha et al., 2017, Janani et al., 2020) and restorative materials.

2) Chronological age: The age of the participants ranged from four to 65 years. The pulp chamber is subject to changes with the advance in age, such as calcifications and the formation of tertiary dentin (Almudever-Garcia et al., 2021). The physiological and morphological variations in the pulp-dentin complex caused inconsistent oxygen saturation measurements in the same tooth location (or tooth group) when considering different age groups. The assumption is that older patients would have lower oxygen saturation levels when assessing the same tooth/tooth group (Stella et al., 2015). However, the considerable methodological differences and the inclusion of a broad age range impeded the researchers from estimating values to serve as parameters for each age group (Estrela et al., 2017a, Estrela et al., 2017b, Lima et al., 2019a, 2019b, Neves Henriques et al., 2022, Pozzobon et al., 2017, Stella et al., 2015, Schnettler and Wallace, 1991, Solda et al., 2018, Souza et al., 2017).
3) Ambient lighting: Two studies reported ambient light as a limitation to the oximetry method (Calil et al., 2008, Kahan et al., 1996). The authors justify this statement by saying that ambient light can interfere with the quality of the signal capture of the device.

3.3. Synthesis of results

Observational-longitudinal-prospective was the most common design (65.8 %). Our analysis found heterogeneity among the studies with regards to the technique for testing tooth pulp status using a pulse oximeter, which resulted in inconsistent estimations of pulp oxygen saturation levels. Overall mean oxygen saturation was 84.99 % for

Table A2
Limiting factors/barriers hindering the use of oximeters in clinical practice reported in the articles which underwent quantitative analysis ($n = 35$). Systematic reviews ($n = 3$) were not included in this table.

Limiting factors/barriers.	Number of articles that mentioned the limiting factor/barrier	Authors/year
Challenges to maintain parallelism between the two light diodes.	$n = 11$	Kong et al. 2016, Sharma et al. 2019, Shetty et al. 2016, Shahi et al. 2015, Oikarinen et al. 1996, Calil et al. 2008, Bargrizan et al. 2016, Schnettler and Wallace 1991, Caldeira et al. 2016, Kahan et al. 1996, Dastmalchi et al. 2012
Patient movement during the oximeter measurement.	$n = 5$	Calil et al. 2008, Estrela et al. 2017a, 2017b, Neves Henriques et al. 2022, Stella et al. 2015, Dastmalchi et al. 2012
Infrared light diffraction by enamel and dentin.	$n = 15$	Krishna et al. 2006, Giovanella et al. 2014, Gopikrishna et al. 2007, Karayilmaz and Kirzioğlu 2011a, 2011b, Oikarinen et al. 1996, Bargrizan et al. 2016, Grabliauskienė et al. 2021, Estrela et al. 2017a, 2017b, Janani et al. 2020, Gopikrishna et al. 2007, Sadique et al. 2014, Neves Henriques et al. 2022, Souza et al. 2017, Stella et al. 2015, Radhakrishnan et al. 2002
Pulp calcifications.	$n = 3$	Gopikrishna et al. 2007, Sadique et al. 2014, Dastmalchi et al. 2012
Large size restorations.	$n = 3$	Karayilmaz and Kirzioğlu 2011a, 2011b, Kataoka et al. 2016, Dastmalchi et al. 2012
Tertiary/reparative dentin.	$n = 1$	Kataoka et al. 2016
Infrared light diffraction by gingival tissues.	$n = 5$	Krishna et al. 2006, Anusha et al. 2017, Janani et al. 2020, Kahan et al. 1996, Radhakrishnan et al. 2002
Patient's chronological age.	$n = 10$	Lima et al. 2019a, 2019b, Giovanella et al. 2014, Pozzobon et al. 2017, Schnettler and Wallace 1991, Estrela et al. 2017a, 2017b, Solda et al. 2018, Karayilmaz and Kirzioğlu 2011a, 2011b, Neves Henriques et al. 2022, Stella et al. 2015, Dastmalchi et al. 2012
Ambient lighting.	$n = 2$	Calil et al. 2008, Kahan et al. 1996
Differences in teeth's external morphological shape.	$n = 7$	Mishra et al. 2019, Lima et al. 2019a, 2019b, Anusha et al. 2017, Calil et al. 2008, Schnettler and Wallace 1991, Stella et al. 2015, Dastmalchi et al. 2012
Differences in pulp's morphological shape.	$n = 3$	Kong et al. 2016, Estrela et al. 2017a, 2017b, Neves Henriques et al. 2022
Teeth under occlusal trauma.	$n = 1$	Giovanella et al. 2014
Technique-sensitive oximeter, need for a specific probe.	$n = 5$	Mishra et al. 2019, Farughi et al. 2021, Sharma et al. 2019, Shetty et al. 2016, Anusha et al. 2017

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Table A2 (*continued*)

Limiting factors/barriers.	Number of articles that mentioned the limiting factor/ barrier	Authors/year
Low reproducibility, different readings compared to other studies.	$n = 3$	Setzer et al. 2012, Estrela et al. 2017a, 2017b, Sadique et al. 2014
Low reproducibility, different readings over short periods of time.	$n = 1$	De La Sotta-Rubio and Gonzáles-Mendoza 2014

sound maxillary anterior teeth and 84.93 % for molars. All phases of the experiments and protocols had considerable variability. Conversely, barriers to the clinical use of pulse oximeters to test pulp vitality were consistently reported by most of the articles included, as follows: 1) difficulty maintaining the oximeter diodes parallel; 2) the diffraction and scattering of infrared light when using the oximeter on oral tissues; 3) differences in the chronological age of the participants; and 4) the interference of ambient lighting.

4. Discussion

4.1. Summary of evidence

Although endodontic therapy has evolved greatly in recent decades, embracing technologies that have improved patient care and guided the field in a new direction, the rejuvenation of pulp diagnostic tools and concepts has been suboptimal (Almudever-Garcia et al., 2021, Gopikrishna et al., 2009, Lima et al., 2019a, 2019b, Mainkar and Kim, 2018). The present scoping review found gaps in knowledge concerning the use of pulse oximeters for testing tooth pulp vitality, especially the inexistence of any device designed and sold specifically for dental and endodontic purposes. This inexistence of a unique 'dental oximeter' is also one of the reasons for the considerable variability among studies with regards to study design, oximeter brand, probe design, independent variables, outcomes measured, etc.

The literature is strong and consistent in recognizing the importance of a pulp test that could measure circulating blood in the vascular tissue rather than measure the response of nerve branches. Moreover, the available evidence is weak in stating parameters/values that may show diminishing oxygen saturation levels within the tooth that would predict pulp degeneration. There are also inconsistent estimations of the pulp oxygen saturation level in sound teeth, which is around 84.9 % (considering all the tooth groups and different age ranges).

After aggregating the findings from the studies in the present scoping review, we identified barriers to the use of oximeters in clinical practice, the most widely reported of which was the difficulty in maintaining the two light diodes parallel during pulp tests. This problem again underscores the need for the development of a specific device (oximeter and probe) designed for dentistry. New developments depend on many aspects, including the will of researchers, policies, partnerships between scholars and industry, and funding. Research cooperation between endodontics and pediatric dentistry would favor the development of a unique device to benefit patients who have undergone dentoalveolar trauma.

The undesirable infrared light diffraction caused by the tooth enamel, dentin, and gingival tissue was also considered a limiting factor for the use of pulse oximeters and customized probes. Crowns, bridges, veneers, and direct composite restorations may interfere with oximeter readings (Stella et al., 2015). Enamel rods and dentinal tubules vary in different individuals, tooth groups, and within the same tooth, as genetic and environmental factors influence the processes of odontogenesis and amelogenesis (Naziya et al., 2019, Pop-Ciutrila et al., 2016). Even a darkened crown due to an injured tooth is considered a potential interference for the passage of light. Manufacturers of different brands of medical pulse oximeters also point out several factors that may cause inaccurate readings due to light diffraction in the patient's finger, such as dark skin pigmentation, thick skin, tobacco use, low skin temperature, and darkly polished nails. Thus, the importance of obtaining and maintaining parallelism between the diodes is again underscored, as the light would have a shorter distance to travel in comparison to inclined paths.

Diversity in patient age in the studies was considered the third major limiting factor. The lack of well-defined oxygen saturation levels for use as a gold-standard for comparisons between different age groups (Shahi et al., 2015) and the lack of patterns of oxygen saturation levels in the same patient over time are drawbacks for using oximeters in dental practice. Therefore, the inclusion of different age groups in the same study and/or the longitudinal investigation of a specific cohort of patients would be key factors to overcome with this limitation. Lastly, studies included in the present scoping review assumed that ambient lighting is a limiting factor to the adoption of oximeters as pulp testers. However, several studies in medicine (including a prospective repeated-measures study and a recent randomized cross-over trial) have proved that ambient lighting is clinically unimportant with regards to the accuracy of medical pulse oximeters (Fluck et al., 2003).

4.2. Strengths and limitations of the scoping review process

A strength of this scoping review was the comprehensive literature search that included all published systematic reviews that met our inclusion criteria (Almudever-Garcia et al., 2021, Lima et al., 2019a, 2019b, Mainkar and Kim, 2018). Although the systematic reviews were not included in the quantitative data analysis to avoid data duplication and consequently the overestimation of findings, these articles supported the authors in assessing the state of knowledge on this topic and recording data in a comprehensive manner. Additional strengths of this review were the ability to identify the types (study designs) of available evidence in the field of pulp oximetry as a pulp test, the clarification of key concepts and definitions necessary to understand the subject (devices, probes, diodes, oxygen saturation, parallelism, etc.), the identification of barriers to the use of the oximetry method in dental practice, and the identification of gaps in knowledge, such as uncertainties with regards to the interference of ambient lighting (Munn et al., 2018).

The limitations of this scoping review are the restrictions imposed on the sample, such as language, geography, and time, which may have resulted in bias. All articles, except one (De La Sotta-Rubio and Gonzáles-Mendoza, 2014), were published in English, which increases the risk of publication bias. Other limitations include a possible failure of our search strategy to identify relevant studies for inclusion and the possibility of data extraction errors.

5. Conclusions

The present scoping review encountered noteworthy findings associated with the impracticability of using medical pulse oximeters as dental pulp testers, such as the difficulty in maintaining the two light diodes parallel when the oximeter is attached to the buccal and palatal surfaces of teeth, the diffraction and scattering of infrared light caused by oral and dental tissues, as well as the lack of well-defined oxygen saturation levels to use as a gold-standard for comparisons between different age groups and the lack of patterns of oxygen saturation levels in the same patient over time. The recent decrease in the frequency of published studies on the use of pulse oximeters as pulp testers compared to approximately seven years ago may imply a negative trend in the feasibility of the method, which uses medical pulse oximeters adapted with customized 'dental probes'. Due to the importance of an accurate pulp test that is more objective (and less subjective), especially for young patients who have experienced dentoalveolar trauma, the development of a specific device (oximeter and probe) for use in dentistry is of the utmost importance. New developments would prompt further research to produce evidence on oxygen saturation levels for different tooth situations, different ages, and different environments.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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