HASAN AL ZAIBAK

Determining tooth vitality by measuring its surface temperature: a systematic review and meta-analysis

São Paulo

2022

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Revised Version

Dissertation presented to the Faculty of Dentistry of Universidade de São Paulo, by the Postgraduate Program in Dentistry to obtain the title of Master of Science.

Concentration area: Endodontics

Advisor: Prof. Dr. Celso Luiz Caldeira

São Paulo

2022

Catalogação da Publicação
Serviço de Documentação Odontológica
Faculdade de Odontologia da Universidade de São Paulo

Al Zaibak, Hasan.

Determining tooth vitality by measuring its surface temperature: a systematic review and meta-analysis / Hasan Al Zaibak; advisor Celso Luiz Caldeira. -- São Paulo, 2022.

106 p. : fig. ; 30 cm.

Dissertation (Master’s degree) -- Postgraduate Program in Dentistry. Concentration Area: Endodontics. -- Faculty of Dentistry, University of São Paulo.

Revised version.

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1. Tooth temperature. 2. Diagnosis. 3. Endodontics. 4. Systematic review. 5. Meta-analysis. I. Caldeira, Celso Luiz. II. Title.

Fábio Jastwebski – Librarian - CRB8/5280

APPROVAL SHEET

Al Zaibak H. Determining tooth vitality by measuring its surface temperature: a systematic review and meta-analysis. Dissertation presented to the Faculty of Dentistry of Universidade de São Paulo to obtain the title of Master of Science.

São Paulo: 07/03/2023

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“We are going to die, and that makes us the lucky ones. Most people are never going to die because they are never going to be born. The potential people who could have been here in my place but who will in fact never see the light of day outnumber the sand grains of Arabia. Certainly, those unborn ghosts include greater poets than Keats, scientists greater than Newton. We know this because the set of possible people allowed by our DNA so massively exceeds the set of actual people. In the teeth of these stupefying odds, it is you and I, in our ordinariness, that are here.

After sleeping through a hundred million centuries, we have finally opened our eyes on a sumptuous planet, sparkling with color, bountiful with life. Within decades we must close our eyes again. Isn't it a noble, an enlightened way of spending our brief time in the sun, to work at understanding the universe and how we have come to wake up in it? This is how I answer when I am asked -- as I am surprisingly often -- why I bother to get up in the mornings. To put it the other way round, isn't it sad to go to your grave without ever wondering why you were born? Who, with such a thought, would not spring from bed, eager to resume discovering the world and rejoicing to be a part of it?”

Prof. Richard Dawkins

ACKNOWLEDGMENTS

I would like to express my heartfelt appreciation to my supervisor, **Prof. Dr. Celso Luiz Caldeira**. I would not be here completing my journey with this research if it had not been for him, his knowledge, and his guidance. The scientific thinking tree grew greater in me through his methods and counsel, paving the road to becoming a good researcher and educator.

I also want to thank **Prof. Dr. Mary Caroline Skelton Macedo** and **Prof. Dr. Laura Cristina Leite Nardello** for their assistance and efforts in bringing the concept of this research to reality through their extensive support and comprehensive experience.

Dr. Manal Zaibak, proudly my sister and best friend, deserves my deepest gratitude. She was essential in completing this research, as she has always played a big part in my life. She is the family I need and the friend who listens when I cannot find any. She has always been there for me in the best and worst moments. From my childhood to this day, she has only shown me love, support, and understanding. I would not be where I am if not for her.

More than that, I am grateful to **Prof. Dr. Patricia Moreira de Freitas** for always being a genuine and empathetic teacher, and for being the first to introduce me to this new world with all the great individuals at this institution.

Finally, I would like to thank my family, friends, professors, and colleagues for their friendship, incredible memories, and knowledge exchanged throughout the years.

ABSTRACT

Al Zaibak H. Determining tooth vitality by measuring its surface temperature: a systematic review and meta-analysis [dissertation]. São Paulo: Universidade de São Paulo, Faculdade de Odontologia; 2022. Revised Version.

Introduction: Diagnosis is a crucial step for determining the treatment. Therefore, accessing pulp vitality is performed in many ways that rely on evaluating the pulp's innervation, which can present numerous limitations. Accessing the pulp vascularity has also been achieved in many ways, none of which is adequate for clinical employment. As a result, the review aims to determine the link between tooth vitality and its surface temperature. A systematic review is a comprehensive and methodical approach that uses explicit methods to identify, select, critically appraise relevant research, and collect and analyze data from studies that are included in the review. **Methods:** Criteria for inclusion and exclusion were established. Using the keywords "diagnosis" and "tooth temperature," 10 electronic databases were searched. After that, the studies were chosen after searching the results. The data was then extracted and placed on an Excel sheet. The significant difference in tooth base temperatures was evaluated. The Joanna Briggs Institute checklist was used to assess the risk of bias. The meta-analysis was carried out using the ‘meta’ package in RStudio. **Results:** After retrieving and processing 4.382 articles, 616 duplicates were deleted. After data extraction, the remaining publications were evaluated, and 14 were included in the systematic review, but only 9 were included in the meta-analysis. Some writers discovered that the surface temperature of vital teeth was higher than that of nonvital teeth, whereas others found no significant difference. The risk of bias assessment indicated that the publications fared well in some domains but poorly in others. The funnel plot, on the other hand, was symmetrical. The overall analysis revealed a significant difference. **Conclusion:** Measuring the temperature of the tooth surface could be valuable in determining tooth vitality. However, additional research is required to confirm these outcomes.

Keywords: Tooth temperature. Diagnosis. Endodontics. Systematic Review. Meta-analysis.

RESUMO

Al Zaibak H. Determinando a vitalidade do dente pela a medida da sua temperatura de superfície: uma revisão sistemática e meta-análise [tese]. São Paulo: Universidade de São Paulo, Faculdade de Odontologia; 2022. Versão Corrigida.

Introdução: O diagnóstico é um passo crucial para determinar o tratamento. Portanto, a avaliação da vitalidade pulpar é realizada de várias maneiras que dependem da avaliação da inervação da polpa, que pode apresentar inúmeras limitações. O diagnóstico da vascularização pulpar também foi alcançado de várias maneiras, nenhuma das quais é adequada para o emprego clínico. Como resultado, a revisão visa determinar a relação entre a vitalidade do dente e a temperatura de sua superfície. Uma revisão sistemática é uma abordagem abrangente e metódica que usa métodos explícitos para identificar, selecionar, avaliar criticamente pesquisas relevantes e coletar e analisar dados de estudos incluídos na revisão. **Métodos:** Foram estabelecidos critérios de inclusão e exclusão. Utilizando as palavras-chave " diagnosis" e "tooth temperature", 10 bases de dados eletrônicas foram pesquisadas. Em seguida, os estudos foram escolhidos após a busca dos resultados. Os dados foram então extraídos e colocados em uma planilha do Excel. A diferença significativa nas temperaturas da base do dente foi avaliada. A lista de verificação do Joanna Briggs Institute foi usada para avaliar o risco de viés. A meta-análise foi realizada usando o pacote ‘meta’ no RStudio. **Resultados:** Após a recuperação e processamento de 4.382 artigos, 616 duplicatas foram excluídas. Após a extração dos dados, as demais publicações foram avaliadas e 14 foram incluídas na revisão sistemática, mas apenas 9 foram incluídas na meta-análise. Alguns autores descobriram que a temperatura da superfície dos dentes vitais era maior do que a dos dentes não vitais, enquanto outros não encontraram diferença significativa. A avaliação do risco de viés indicou que as publicações se saíram bem em alguns domínios, mas mal em outros. O gráfico de funil, por outro lado, foi simétrico. A análise geral revelou uma diferença significativa. **Conclusão:** A medição da temperatura da superfície do dente pode ser valiosa na determinação da vitalidade do dente. No entanto, pesquisas adicionais são necessárias para confirmar esses resultados.

Palavras-chave: Temperatura do dente. Diagnóstico. Endodontia. Revisão Sistemática. Meta-análise.

SUMMARY

1 INTRODUCTION

Diagnosis is one of the most crucial aspects in endodontic treatment. It is described as the science of detecting pathological conditions by means of signs, symptoms and examinations. Even though it is a science, it is not without flaws. A thorough, conclusive diagnosis is not always simple to get. It usually entails a thorough examination (1).

The primary goal of establishing an accurate endodontic diagnosis is to determine the clinical treatment required. As a result, formulating an opinion about the pulp condition can be viewed as a composition of all the required information that the practitioner can acquire to make the most probable diagnosis (2).

In the dental profession, assessing pulp vitality is critical. That is why Ehrmann (3) differentiated between two types of diagnoses. The first one is the diagnosis of pain, which can be caused principally by pulp pathology. That sometimes can be challenging due to the possibility of no radiographic evidence and the referred pain in a different area. According to one paper, sinus inflammation can cause pain or pressure in the posterior maxillary teeth (4).

The other type is the diagnosis of radiolucent regions, which are found most commonly at the apex of the tooth. Such lesions are typically caused by pulp degeneration and loss of bone in that area. Bender observed in one investigation that the lowest percentage of cortical bone loss required to produce a radiolucent area on a radiograph was 12.5%, with 6.6% mineral bone loss (5).

However, to truly comprehend the pulp vitality evaluation, we must first assess the limitations of modern methodologies. As a result, one must be familiar with Chambers' description of the perfect pulp tester. The ideal approach should give a simple, objective, standardized, reproducible, non-painful, non-injurious, precise, and low-cost procedure for examining the pulp's state at any moment. Unfortunately, none of the current means meet the specified criteria (6).

The clinical diagnosis of the abnormal status of the dental pulp is not attainable, and this is carried out only through histological exams. Most of the currently used vitality tests are too limited in this regard. Many studies have shown a poor correlation between clinical signs and symptoms and histological findings (7,8). One of the reasons is that the inflammation or necrosis in the pulp can be partial or total, it can extend to one canal in the multi-rooted tooth without the other. So, this may give confusing results during the clinical examinations (9).

The most popular pulp tests are based on the patient's subjective response, whether they can feel a specific "sensation" in the tooth, which can be uncomfortable even for some. Thus, they lack objectivity and cannot always be reliable in determining the condition of the pulp (10). King even argued that the patient's mental and emotional state influences his response (11). In addition, pain thresholds vary individually, so the patient's cooperation is critical to the exams (3). According to one study, while most patients could accurately identify the arch and side of the pain when diagnosing irreversible pulpitis, only 73.3% could correctly identify the painful tooth. The paper also noted that the patients who were unable to recognize the involved tooth reported more intense pain than the other group (12).

One of the main limitations of the electric pulp tests is that their use is inappropriate when a full coverage crown or orthodontic braces are present, nor in immature permanent teeth. In the last case, the cold test with CO2 or refrigerant spray is more suitable (13,14) . Moreover, it is crucial to note that these tests are not always appropriate for teeth that have had dental trauma. The tooth's nerves might become severed because of the trauma or go through functional derangement, whereas the pulp retains its vascularity. Bhaskar et al. (15) reported the observations on 25 teeth that had undergone dental trauma. They did not show any positive response on electric or thermal testing, but they did have vital pulps after accessing the pulp chambers. As a result, after trauma, teeth should be regarded vital until shown otherwise by the development of an apical radiolucency or a sinus tract. This fact underlines an essential aspect of the conventional dental pulp tests. They evaluate tooth sensitivity by the status of the teeth's nerves rather than assessing the vascularity of the pulpal tissue, which is more critical and characterizes its health.

However, as research into the physiology of the pulp progresses, numerous authors have experimented with measuring pulp vitality by vascularization rather than pulp sensibility. Even though none of these approaches are currently used in clinical practice, they include spectrophotometry (16), photoplethysmography (17), laser doppler (18,19), and pulse oximetry (20,21).

Furthermore, assessing tooth temperature for endodontic diagnostics follows the same logic. It is thought that the pulpal blood flow, along with other factors, contributes to the temperature of the tooth, so measuring the temperature of the tooth is supposed to assess its vitality. Many devices were utilized in the literature to achieve this goal. However, the results in this regard have been inconsistent and inconclusive over the years. As a result, this study investigates the relationship between tooth temperature and vitality and evaluates the existing evidence for this approach as a diagnostic tool in dentistry, particularly endodontics.

2 LITERATURE REVIEW

Formulating a precise diagnosis is the most critical step before proceeding with operative procedures. The patient's history of pain is essential to establishing a provisional diagnosis before further investigations. According to Baume, the indication for proper endodontic therapy is determined by the etiology, pathology, and symptomatology, which serve as the foundation for any differential diagnosis (22) . Indeed, Ehrmann emphasizes the significance of vitality tests, stating that no oral diagnosis can be completed without measuring the pulp vitality of all the present teeth (3).

Many subjective and objective clinical examinations can be employed to access the vitality of the pulp, which should not be used to measure its health or disease. Nevertheless, they provide diagnostical information that no other examinations can (6).

Some of the pulpal tests accomplish this indirectly by accessing the nerve pathways in the pulp, while others examine the vascular supply. Sometimes a group of these examinations can be invasive to the dental or adjacent tissues.

2.1 Invasive Pulp Sensibility Tests

2.1.1 Cavity Preparation

The cavity test is probably the least employed approach and the most invasive. Even though it is an irreversible procedure, some authors suggested it in cases of inconclusive diagnosis and when all other methods showed few results. Such a case may occur in teeth with full crowns, as an electric pulp tester or cold test are likely to be less accurate. Performing the test consists of drilling through the crown or enamel with a small-sized round diamond burr in the high-speed hand-piece until reaching the dentin; all steps should be through proper cooling and using a rubber dam. Usually, the patient is not anesthetized. If there is pain or discomfort when in contact with sound dentin, the procedure should be terminated and the cavity restored. If the operation exposes the pulp chamber without any experienced pain, then pulp necrosis is probable, indicating a root canal treatment. The related sensation only suggests that some viable nerve still exists in the pulp, which does not guarantee that the pulp is perfectly healthy. Neither does it inform about the pathology of the pulp and its extension. The use of the cavity test in clinical practice is unreliable, and scientific evidence does not support its efficacy. Furthermore, allowing a young patient to endure this procedure may have long-term negative consequences. Under the circumstances based on the patient's best interests in modern endodontics, test cavities are neither appropriate nor justified (23–25).

2.1.2 Local Anesthesia

When symptoms are vague, the patient is uncertain which tooth or arch is causing the pain, establishing a diagnosis can be challenging. If the other vitality tests did not give positive results, the selective anesthesia test might be advantageous in these circumstances. It can aid the health care practitioner in locating the pain and identifying the potential tooth group involved. When a patient is unsure of which arch is causing pain, the dentist should begin by relieving the maxillary side. Then, one tooth at a time, the injections are given starting from the distal of the most posterior suspected tooth until the patient no longer experiences pain. Then repeating the procedure is recommended in the mandibular teeth if the pain is still present. However, it is commonly confused that the periodontal ligament injection only anesthetizes a single tooth. Walton demonstrated that this procedure is an intraosseous injection that affects many teeth. Therefore, using this method to identify the arch is more appropriate than specifying a single tooth (26,27).

2.2 Non-invasive Pulp Sensibility Tests

2.2.1 Thermal Pulp Tests

Assessing the pulp's responsiveness to thermal stimulation involves many methods and materials. It is typically a straightforward process that does not require any costly technology. It can, however, provide the practitioner with vital knowledge about the state of the pulp. The natural response to a cold or heat test is for the patient to observe that a sensation is felt but quickly disappears after removing the thermal stimulus. The abnormal stimulus responses may include pain that persists or worsens after taking away the stimulation, a terribly unpleasant and abrupt sensation when placing the test on the tooth, or a complete lack of response or feeling. Before initiating the procedure, the examined tooth should be isolated with cotton rollers and dried.

Cold testing is the primary pulp testing choice among many professionals. It is administered in many forms and is especially effective for patients with teeth that do not have a natural surface exposed due to full coverage crowns. According to Miller et al. (28), when three different methods, ice sticks, carbon dioxide, and 1,1,1,2-tetrafluoroethane, were tested, the last produced the quickest reduction in the temperature of the teeth with full coverage crowns.

If the contralateral tooth is sound, evaluating it first so the patient can understand the nature of the stimulus and establish a baseline response would be wise. When compared to healthy teeth, inflamed teeth respond intensely. If ice sticks are chosen for the test, a rubber dam should be used since melting ice will run onto adjacent tissues, giving false-positive results. The test usually is applied on the middle third of the buccal face of the teeth. If vital pulp tissue is present in the tooth, frozen carbon dioxide (CO2), also known as dry ice, carbon dioxide snow, or CO2 stick, has been demonstrated to induce a positive response reliably (29).

However, the refrigerant spray is the most utilized method for cold testing. It is widely available, simple to use, and offers consistent results. In assessing pulpal responsiveness, V. Jones showed that refrigerant spray and CO2 provided similar findings, even though the refrigerant spray induced a more rapid response (30).

The spray can be utilized through numerous carriers. D. M. Jones demonstrated in one study that the large cotton pellet produced the coolest temperatures inside the pulp of the tooth by a range of 35°C to 45°C, compared to a small cotton pellet or cotton applicator. It enables a larger surface area to be placed on the tooth while preventing the wicking effect (31).

On the other hand, another pulp testing method involves using heat to induce a response through a rapid change in the temperature of the tooth. This test is ideal when the patient's chief complaint is a pain when consuming hot beverages or food. It is desirable to conduct it in the same pattern as the cold test procedure, starting from the last posterior maxillary teeth and isolating each tested tooth. The expected response is to have a sensation when the stimulus is applied that immediately stops when removing it. Because a postponed reaction is plausible when performing the heat test, waiting a few seconds before repeating the test is beneficial. According to Bierma et al. (32), many methods and substances are employable for the test, including hot water, a heated instrument, heated gutta-percha, or a heat-testing tip, with the latter providing the most consistent results when compared to the others. Furthermore, utilizing hot water or instruments is not recommended because the procedure is usually unpredictable and can cause thermal damage to the pulp and adjacent tissues. When choosing heated gutta-percha or wax stick for the procedure, a layer of Vaseline or other lubricant is advantageous since it prohibits the material from sticking to the surface of the examined tooth.

Rickoff et al. (33) studied the histological effects on the pulp after applying thermal tests to the mid-buccal surface of the teeth, such as hot gutta percha for 10 seconds and carbon dioxide snow for up to 5 minutes. The temperature of heated gutta percha can reach 76°C, whereas the temperature of CO2 can reach -78°C. After introducing the substance to the teeth, they were extracted, sectioned, and histologically analyzed. The study showed that the thermal tests did not drastically change the temperature of dental tissues, nor did they subject the pulps to any pathological alteration.

2.2.2 Electric Pulp Test

The electric pulp testers are appropriate for detecting the viable sensory nerve fibers in the pulp by eliciting an electric current, which indirectly determines the pulp vitality. They are all based on the generation of negative-polarity impulses, which are said to lower the voltages required to stimulate a pulpal response and avoid the excitability of the nerves in the periodontal membrane (34).

The device's functionality depends on its conductive contact with the natural tooth structure. Because it is critical to coat the tip of the testing probe with water or a petroleum-based media, toothpaste is popular for achieving this objective. The coated probe tip is then positioned into the incisal third of the facial or buccal area of the tooth to be examined (35,36).

When not utilizing a lip clip to complete the electric circuit, the practitioner instructs the patient to touch or grab the tester probe once it has made contact with the tooth. This process completes it and starts the flow of electricity to the tooth. When the patient feels a tingling sensation in the tooth, they are instructed to remove their finger(s) from the probe. The physician cannot complete the circuit due to operating with rubber gloves. The evaluation of the response is based on whether it exists or not. In most cases, a lack of response implies that the pulp is necrotic. It depends on the subjective judgment of the patient, which can result in an incorrect diagnosis. Because there is no link between device values and histological tests, the approach does not help determine the type of pathological process present in the pulp. However, it can be highly effective for assessing whether the pulp is vital or not (37,38).

It is impossible to make an accurate diagnosis using only one exam or one sort of data. Combining the patient's history with multiple vitality tests is desirable. According to Peters et al. (39) , a negative response to both of the electric and cold tests nearly always indicates a necrotic or pulpless tooth. Weisleder et al. (40) have also shown in another study that combining the electric and cold pulp test improves diagnostic accuracy.

2.3 Invasive Pulpal Blood Flow Tests

2.3.1 Radioisotope Clearance

Xenon has been utilized to measure blood flow in numerous human tissues, including the gingiva. After entering the bloodstream, the chemically inert gas is readily diffusible in blood and tissues, emits a detectable gamma photon, and is removed promptly by the lungs. Kim et al. (41) measured pulpal blood flow with the same chemical in one of the investigations on 21 animals. The xenon washout method is an application of the law of matter conservation. The prepared tooth received a scintillation probe on its surface then the substance was injected into the pulp via the maxillary artery. The xenon attained peak activity inside the pulp 5 seconds after the injection. Then within 10 minutes, the tissue only contained 10-15% of the remaining concentration. An equation was used to calculate the blood flow per unit mass of pulp tissue. They repeated the experiment with ten teeth as control measurements, and the results were very reproducible. The approach can be beneficial for monitoring blood flow and its pathology in the pulp and studying the impact of dental products or procedures. However, it is complex and has only been investigated on animals.

2.3.2 H2 Gas Desaturation

Researchers have long been interested in pulpal blood flow studies. The blood flow was measured using the H2 gas desaturation method. In one study, Tönder et al. (42) used this compound to evaluate pulpal blood flow. The study included 15 canine subjects who had been prepped accordingly for the assessment. Then the electrodes were placed into the pulp through buccal drilled perforations before sealing the exposures. The implantation of the electrode wire was subcutaneously several centimeters away from the tooth. A chronic tracheal cannula was employed to deliver the gas. Even though the authors propose the approach for measuring pulpal blood flow, definitive validation of absolute values is still absent. Furthermore, the electrode insertion element may cause inflammation and abnormal dentine development around the electrode, which probably impairs blood flow measurement accuracy due to inflammatory infiltration.

Omoto et al. (43) evaluated the pulpal blood flow and the building up of specific metals inside the pulpal tissues in another study that utilized the same procedure on canine subjects. They discovered that the pulpal blood flow differs between maxillary and mandibular teeth and whether they are temporary or permanent, which means that it depends on the age of the subjects. Furthermore, a clear association exists between pulpal blood flow and the accumulation of the metals provided. The authors concluded that the hydrogen gas clearance approach is appropriate for evaluating minimal quantities of local blood flow on a small-scale level.

Heyeraas et al. (44) employed H2 to monitor the pulpal blood flow in reimplanted teeth in animal subjects in another interesting study. They had measurements 6, 10, 16, 21, and 28 days (about 4 weeks) after the procedure. The authors noted that, after reimplanting the teeth, none of the original pulps remained. They developed necrosis that was followed gradually by pulpal repair and replacement of the injured tissue via proliferation of mesenchymal cells and capillaries through the apices. Furthermore, there was no detectable blood flow in the cervical region at 6, 10, or 16 days (about 2 and a half weeks). Contrary to multi-rooted teeth, the coronal pulps of single-rooted teeth were never revascularized.

2.4 Non-invasive Pulpal Blood Flow Tests

2.4.1 Laser Doppler Flowmetry

Laser doppler flowmetry (LDF) is a method developed to measure blood flow in the microvascular systems, like the retina, skin, and renal cortex. In this manner, examining pulpal blood flow through the same technology also seems efficient. A diode directs an infrared laser beam through a tooth's crown and pulp chamber. The pulp tissue scatters the infrared light beam as it travels through it. The scattered light beams from moving red blood cells are frequency-shifted according to the Doppler principle, whereas those from static tissue are not. The average Doppler frequency shift will determine the red blood cells' movement speed (45,46).

Gazelius et al. (18) demonstrated in his paper measurements of the vascularity of vital and non-vital teeth with laser doppler. They concluded that when compared to the contralateral tooth, the output signal from non-vital teeth was close to the background. Therefore, the LDF signal reflects microcirculatory events in the pulp, which is beneficial in teeth that have undergone trauma and are not responding to vitality tests.

Wilder-Smith conducted another study that demonstrated the efficacy of Laser Doppler Flowmetry in monitoring pulp blood flow. When they examined the pulps under active dentinal cariogenic lesions, they discovered that the active lesion caused an increase in pulpal blood flow, which returned to normal after treatment. That illustrated the pulp's capacity to repair (19).

Yanpiset et al. (47) performed one of the first investigations on the revascularization of reimplanted teeth on animal subjects using Laser Doppler Flowmetry. The method displayed remarkable promise for detecting the vascularity of the pulp with high accuracy in examining non-vital teeth more than vital ones. The fourth week witnessed blood flow return to the reimplanted teeth, which continued to increase until the 12th week.

As a result, unlike other vitality tests that evaluate the tooth's nerve supply, LDF appears to be an accurate and dependable tool for accessing pulp vitality based on objective observations of blood flow to the tooth. However, it is still not widely used in dental practice due to its high cost, lack of reproducibility, and sensitivity to motion (48).

2.4.2 Pulse oximetry

The pulse oximeter is one of the most applied non-invasive monitoring devices for measuring patients' oxygen saturation and pulse rate. Many models are available, but they all work on the same concept. When light passes through a photoelectric diode and into a receptor, the difference between the emitted and received light provides information about the pulse rate and oxygen saturation levels. The diode emits two wavelengths of light, red (640 nm) and infrared (940 nm), which detect arterial and venous blood. The ratio of light absorbed provides the percentage of blood oxygenation. Schnettler et al. (20) established the accuracy of this method for determining pulp vitality.

From day 0 to six months following the trauma, one study compared pulse oximetry with electric and cold pulp testing for recently traumatized maxillary incisors. When the other methods yielded negative results for the first 21 days (about 3 weeks), the pulse oximeter provided consistent readings of intact vascularity in the pulps. On the 28th day, up to 3 and 6 months, more teeth showed signs of vitality using the electric and cold tests (49).

Another study investigated the pulse oximeter's ability to distinguish between healthy and pathological pulp conditions, such as pulp necrosis and reversible and irreversible pulpitis. The authors showed significant statistical differences in the mean pulp oxygenation levels for each pulpal condition, which could be a way to detect abnormal processes occurring inside the pulp (21).

2.4.3 Photoplethysmography

By incorporating a light with a shorter wavelength, photoplethysmography enhances the concept of pulse oximetry as it studies changes in tissue opacity with little to no trauma to the tooth. A photocell and an optical fiber measure the light as it travels through the tooth and determine its current wavelengths. The blood's hemoglobin selectively absorbs wavelengths. The device analyzes the unabsorbed light and measures pulpal blood flow. Vasoconstriction of the arteries, such as cold-induced, would increase arterial transmural pressure, decrease interstitial pressure, and make it easier for blood capillaries in the dental pulp to fill with blood. As a result, less light will pass through the dental pulp, which will cause the baseline of the photoplethysmogram to shift upward and the amplitude of the pulse waves to increase. Venous congestion would produce the same decrease in opacity effect as well as the increase in arterial transmural pressure (17).

The technique has been applied to the pulps of cats and dogs as it showed promise for analyzing changes in pulpal blood flow. Neidle et al. (51) observed that pulpal blood flow is influenced by several variations, whether those variations impact the local or systemic levels. Among them is the administration of adrenergic, smooth-muscle relaxants, or vasoactive drugs (50–52).

A different study by Miwa et al. (53) showed that, even though photoplethysmography measurements are not quantitative, readings on developing permanent teeth could detect pulpal blood flow, in contrast to non-vital teeth. Contrary to laser doppler flowmetry, using a rubber dam did not significantly reduce the signals recorded, and there was less noise from periodontal blood flow.

2.4.4 Dual Wavelength Spectrophotometry

Dual wavelength spectrophotometry is a technique based on the core concept that each substance absorbs or transmits light at specific wavelengths. By examining the amount of unabsorbed light that a detector is receiving, it can determine how much a compound absorbs light. Even though pulse oximetry requires a pulsatile blood flow in contrast to this method, it follows the same principle. The light emitting in two wavelengths, (760 nm) and (850 nm), is used to measure changes in volume and oxygenation. According to the findings, there is good reproducibility. Only initial in vitro studies, though, were reported (16).

2.4.5 Tooth Temperature

The difference between heat raised to the tooth's surface and heat lost to its surroundings determines the temperature of the tooth's surface. It is believed that multiple sources, including dentine and enamel from periodontal tissues, as well as the pulp's vascularization and metabolic activity, contribute to the vital tooth temperature. Non-vital teeth are thought to only receive heat from the tissues around them, which implies that in diagnosing pathological statuses, the difference in temperature between vital and non-vital teeth could offer essential aspects about the condition of the underlying pulp (54).

Fanibunda offered a rationale for temperature-based clinical pulp diagnosis in one of his studies. Compared to supporting tissue circulation, he demonstrated that pulpal circulation was more efficient at regulating the temperature of the crown regarding its surroundings. The researchers built a unit from an extracted tooth to reach these results. The module circulated a fluid as the pulp and consisted of an acrylic pouch around it as the surrounding tissues. Two tiny tubes acted as input and outlet in each of the components for the circulatory fluid, which was regular saline maintained at the temperature of 37°C. A thermistor measured the temperature by contacting the enamel of the extracted tooth (55).

2.5 Devices for Measuring the Temperature

There are numerous methods for measuring tooth temperature. Some are still in use today, while others are no longer recommended.

2.5.1 Thermocouple

Thermocouples are well-known for their dependability and efficiency in monitoring temperatures ranging from -270°C to 3000°C. They are inexpensive, simple, durable, and can detect a wide range of temperatures. They have a quick response time and excellent sensitivity, although they are less precise than resistance temperature devices. The devices are based on the Seebeck effect, which involves the formation of an electromotive force in a circuit consisting of two different conductors exposed to a thermal gradient. There are four types of thermocouples: noble metal, base metal, high temperature or refractory metal, and nonmetal (56).

Brown and Goldberg measured the surface temperatures of teeth using thermocouples. A thin piece of adhesive tape a little bigger than the tip fixed the instrument to the tooth. The tip that was bare had a 40-gauge conductive material soldered, which constructed the thermocouples. It had a diameter of around 0.2 mm (about 0.01 in). Then the authors employed two thermocouples; one on the tooth and one in the reference solution. It was observed that the cooler the tooth, the more anterior and closer to the midline. Furthermore, the palatal surface was generally warmer than the vestibular surface (54).

2.5.2 Thermistor

The thermistor is a compact, cheap temperature resistance device made modernly of metals and doped ceramics. It is composed of a semiconductor with temperature-sensitive resistance. Various reasons made the thermistors suitable in the biological field, including their high sensitivity to slight temperature changes, efficient thermal transmission, long-term stability, and innate durability. In addition, they come in different shapes and sizes. The accuracy of these devices can range from 0.01 ° C to 0.05 ° C, with commercially available units having an accuracy of roughly 1 ° C. Their downside is that their calibration is susceptible to alteration owing to changes in semiconductor materials (56,57).

Many studies used a thermistor to measure the surface temperature of the teeth. Banes and Hammond used a thermistor thermometer to detect heat.

When measuring a surface, the sensitive element must be at the same temperature as the surface measured, and its presence must not modify the item's temperature. Placing the thermistor on a hand shaped like a dental contra-angle handpiece made it easier to use. Its availability, accuracy, stability, remote reading, and battery power source made the YSI Model 43 Tele-thermometer a good choice. The equipment worked well for measuring tooth temperature (58).

In many of his experiments, Fanibunda also used a thermistor unit. It consisted of two thermistors connected back-to-back, one of which touched the enamel surface to record the temperature of the crown and surroundings, while the other remained suspended in the air near the first and recorded the ambient solely. Because both thermistors recorded the atmosphere's temperature, their influence was balanced out, leaving only the temperature of the crown to be measured. The authors concluded that this method could be efficient for measuring tooth temperature (55,59).

Smith et al. (60) used the same arrangement but added one thermometer on the tooth's buccal surface, where two thermometers were present; one between the cervical and middle thirds and the other between the middle and incisal thirds. The third thermistor did not contact the tooth surface and left to measure the atmosphere.

Stoops et al. (61) chose thermistors for the study because of their great sensitivity and availability as small sensing units with a minimal potential to store heat and delay its transmission. The instrument proved so sensitive that even a tiny bit of saliva or a change in the room air may impact the performance. Due to the small size of the thermistor, a thin coat of insulating varnish to avoid electrical and mechanical damage proved beneficial. According to the authors, the reproducibility of the approach for measuring tooth temperatures proved accurate.

2.5.3 Cholesteric Liquid Crystals

Since thermal mapping was the first successful application that attained widespread use, liquid crystals utilization as thermal bolometers has been well established and proven effective in medical fields. Liquid crystals have a molecular structure halfway between a crystalline solid and an isotropic liquid. They are called after the phase that form from breaking the bonds between molecules when heated and, as a result, react to temperature changes with a reversible color change. In 1922, Friedel proposed that this phase be called "mesophase" due to the Greek word "mesos," which means intermediate. During this mesophase, the molecules take on a variety of colors depending on the temperature. They become colorless both before and after it. Because of their organic origin, these cholesteric crystals deteriorate when exposed to ultraviolet light and are susceptible to chemical contamination. Because of this, the crystals are encased in polymer spheres. A video camera records the changes in colors, which are saved in the form of primary colors RGB (56,62,63).

In their experiment, Howell et al. (64) utilized liquid crystals to observe the temperature of the tooth. The target mesophase was between 30 and 40 ° Celsius. Therefore, the researchers combined several liquid crystals until they attained the desired range. The colors were then calibrated based on the temperatures that produced them using a thermistor and a thermocouple. They were colorless, red, orange, yellow, green, blue, then colorless when they reached beyond the mesophase. According to the authors, this method could determine pulp vitality when other methods fail.

2.5.4 Infrared Thermography

Thermography is a scanning method that produces a photographic representation of the temperature variation of the body's surface. The thermograph is a device that detects heat emission in the infrared region of the electromagnetic spectrum. This field's progress has led to its efficacy in medicinal applications (65).

Hardy et al. (66,67) explained the physiological importance of infrared emission from the human body in 1934 and claimed that human skin might almost be a blackbody radiator. He revealed the diagnostic value of infrared temperature measurement, laying the foundation for adopting infrared thermography in clinical medicine.

Infrared thermography bases its function on the fact that any object with a temperature greater than -273 ° C emits infrared radiation in response to the vibrations and rotations of the molecules that compose the body. As a result, assessing the temperature of an object using its infrared output is feasible. Therefore, unlike x-rays or y-rays, the approach does not penetrate the tissues of the object examined (68).

Crandell and Hill were the first to examine the implementation of infrared thermography in dentistry. Their equipment has a temperature range of 70 to

110 degrees Fahrenheit with a sensitivity of 0.2 degrees. They aimed to detect periapical abscess by measuring the temperature in the area of inflammation and discovered that it is warmer than the surrounding area. However, thermography revealed just a minimal amount of evidence for the abscess with the mouth closed. An attempt to open-mouth reading was ineffective (69).

Since then, there has been increased interest in using infrared thermography to diagnose oral diseases and determine pulp vitality.

Hartley et al. (70) utilized an infrared camera and an infrared radiometer in his investigation to assess temperatures based on infrared radiation. Both have a mechanism that can read heat energy and then process it with an infrared detector to transform it into a meaningful electrical signal. On the other hand, the camera is best for observing temperature trends over a wider area, whereas the radiometer focuses on a single point in a specific location.

Pogrel et al. (71) measured the temperatures of the teeth using an infrared thermal video system. The camera could detect temperature changes as little as 0.1°C at various distances from the subject. The scientists discovered that the teeth' temperature was affected by many factors that could alter it, such as the mouth breathing of the patient. Orthodontic bands were colder than the teeth. Therefore, the authors concluded that infrared thermography employing a close-up lens is an accurate way of detecting minor temperature changes in the teeth.

In their investigation, Mendes et al. (72) used an infrared camera capable of taking very accurate readings from 0.2 m. While the patients were lying on the dental chair, the examinations were in a room with controlled temperature, steady humidity, and relative isolation for the teeth. Since different pulp conditions produce different temperatures, the scientists suggested that infrared thermography could aid in diagnosing vitality in traumatized teeth. However, the procedure had some constraints, including controlling the amount of saliva generated during the exam, mouth breathing, dental crowding, tooth inclination, and a low reach for posterior teeth. The authors suggested scanning the occlusal or palatal surfaces of the posterior teeth.

In a clinical study, Kamath and Nasim used a laser-guided infrared thermometer device to test pulp vitality. The examined object emits radiation, and when the laser beam is directed at it, it endures a change in its wavelength. The laser beam is then returned to the device and detected by a sensor, which records the difference between the reflected emitted radiation. This method yields numerical numbers that correlate to the surface temperature. The instrument is highly accurate, measuring temperatures ranging from -30 ° C to 650 ° C. It was found that laser-guided infrared thermography is a reliable technique that could be implemented in routine clinical settings (73).

2.6 Physiology of the Dental Pulp

The mature dental pulp is the tissue found inside the tooth. It is formed originally from the ectomesenchyme and resembles the embryonic connective tissue. The essential role of the pulp is developing the tooth as it gives rise to vital components like dentin and enamel, and afterward, when damage occurs, it plays a part in the development of reparative dentin. The pulp is heavily innerved with sensory nerves and richly composed of micro-vessels and collagen fibers. It is confined physically within a rigid calcified cavity that prevents it from expanding. Due to these factors, pulpal pathophysiology involves complicated mechanisms involving cell interactions with numerous molecular mediators. Microorganisms and their toxins can enter the pulp through caries, fractures, fissures, and exposed borders of restorations. Injuries and infections cause pulpal diseases, which can progress and spread to neighboring tissues, such as the alveolar bone, through the apical foramen. Therefore, it is essential to understand the healthy mechanism of the pulp and its structures to evaluate the pathological changes (1,74).

2.6.1 Vascularization of the Pulp

Regarding the pulp microcirculation, the pulp consists of arterioles and venules with diameters below 100 µm and 200 µm, respectively. The external carotid artery supplies all of them through its branch, the maxillary artery that leads to the dental one. The micro-vessels enter the tooth pulp through the principal and accessory apical foramina. The principal arterioles tend to be in the center and pass longitudinally towards the coronal pulp. They send out branches to create the extensive sub-odontoblastic capillary network at the periphery of the pulp, which provides the odontoblasts with the necessary nutrients. Then at the center of the pulp, the blood flows into venules arranging a hierarchical system, from arterioles to capillaries to venules. Some arterioles, particularly in the root canal areas, create U-turn loops that may play a role in regulating the pulpal blood flow. Venules take up most of the space in the pulp's center. They have thinner walls, despite being larger than collateral arterioles. The blood in the dental pulp has a comparatively high flow compared to other oral tissues and skeletal muscle (75,76).

2.6.2 Innervation of the Pulp

As to the pulp innervation, several hundred nerve fibers arranged as bundles exit each tooth from the apical foramen. The sensory impulses from the teeth carried by the trigeminal nerve or the fifth cranial nerve transmit through its mandibular and maxillary divisions, along with other supplemental mylohyoid, lingual, buccal, and auriculotemporal branches. The classification of the peripherals nerve fibers is usually according to the conduction velocity and axon diameter. Group A, with its sub-divisions (α, β, γ, δ), and group B are myelinated where the impulses jump from one node of Ranvier to another in what is known as "saltatory conduction." Whereas the narrowest axons of group C are unmyelinated where the signals transmit throughout the axon as a wave in what is known as "continuous conduction." Most of the axons in the pulps of the teeth are unmyelinated (group C), while the myelinated rest are the smallest of group A-(δ) along with some larger axons like A-(β). A tiny percentage of the unmyelinated fibers, around 10%, are sympathetic efferents. Their activation induces vasoconstriction and, as a result, a decrease in pulpal blood flow (77–79).

Because of their peripheral location, low excitability threshold, and fast conduction, the A-(δ) and A-(β) fibers generate immediate sharp pain in response to external stimuli without any tissue damage proposedly. Moreover, due to their higher excitability threshold and slow conduction, the smaller C fibers create a gradual, dull, and delayed pain associated with pulp injury and the inflammatory process (80).

2.6.3 Pain of the Pulp

Dentine stimulation causes pain, although the mechanism by which this occurs is widely controversial, the theory of hydrodynamics is supported and accepted to explain the dentine sensitivity and pain in the teeth. It proposes that tactile, heat, electric, or osmotic stimuli cause slight movements in dentinal fluid or tubule contents, which excites the nerve endings in the pulp. As a result, pressure on the contents of the tubule has typically been the principal cause of pain. What causes the effect of temperature variations is the contrast between the dentine and the fluid in the tubules and pulp's coefficients of expansion, as presumably that the tubular fluid's coefficient of expansion is at least ten times greater than that of the tubule wall. The theory implicitly assumes that the dentinal tubules are open. For instance, sclerosis-affected dentinal tubules are not sensitive because they cannot allow fluid passage. In other words, dentin that is impermeable should be insensitive. It appears that there are two basic categories of pain-producing stimuli. The more frequent is that which results in an outward flow of tubule fluid by capillary forces induced by the fluid loss at tubule openings or, in the case of cold, through a contraction. Like an effect is created by stimuli such as an air blast, scraping, drilling, or setting sugar onto the dentine. The other type causes a pulp-ward motion of the tubule fluid. That could result from applying heat, for example. Both kinds of stimuli appear to cause a fast movement of fluid, and it is possible that this movement, rather than the relatively tiny pressure changes that may occur, is a sufficient stimulus to the nerves (81,82).

When more extreme temperature variations are delivered to the tooth's crown, thermal stimuli, such as heat or cold, produce superior pain responses since the fluid within the dentinal tubules travels in a quicker or stronger pulse. Gradual temperature change does not generate an instantaneous pain response; the dentine fluid does not move at a high velocity, which is crucial to stimulate the A-δ fibers. Eventually, a reaction occurs when the continuous temperature alteration activates a thermoreceptor with a C-fiber response (83,84).

The odontoblasts compose the dentin and its contents throughout the tooth’s life. The dentinal tubules are packed densely in S-shaped curvatures and 1 to 3 μm in diameter. They dwell in diverse densities according to their location in the crown or the root. There are around 55,000/mm2 tubules close to the pulp, while roughly 15,000/mm2 in the peripheral areas of the dentin. In addition, they allow dentinal permeability to fluids as well as bacterial invasion (85,86).

2.6.4 Damage of the Pulp

Pulp damage happens due to several reasons. However, bacteria and their toxins are probably the most common cause of pulpal injury since the oral cavity is saturated with pathogens and microorganisms. Bacterial invasion can happen through carious lesions, open cavities, or leakage to dentinal tubules under restorative fillings. The dental pulp can develop innate and adaptive immune reactions to inactivate and resist the bacteria and their products that obtain access throughout the lesions. The enamel on sound teeth prevents bacteria from invading the dentine and reaching the pulp, serving as a protective shell. Carious demineralization of enamel caused by acidic chemicals of specific bacterial populations results in barrier collapse and cavitation. Furthermore, a steady outward flow of dentinal fluid pushes away the progressing bacteria. The persistent Gram-positive bacteria that predominate the microflora, such as streptococci, lactobacilli, and actinomyces deteriorate the dentine (87,88).

Other than biological reasons, dental procedures such as improper cooling during deep operative treatment, restoration polishing, or using thermoplastic materials can be stressors that induce thermal injuries to the pulp. According to one study, more than half of the tested healthy pulps did not recover when subjected to a heat rise of 11.1 ° C. The temperature that exceeded that almost always impaired the pulp (89).

Additionally, the teeth can go through mechanical loss that, therefore, exposes the dentinal tubules. That can vary from macro to micro fractures as in dental traumas or cracked tooth syndrome, inadequate dental procedures as in irresponsible tooth preparation or damaging the adjacent teeth, and pathological wear as in attrition or abrasion (90–93).

Furthermore, chemical factors can also harm the pulp and open the dentinal tubules. Such a factor is dental wear by erosion, which can happen due to extrinsic dietary or intrinsic gastric acids. Other factors might include the types of cement used in etching or deep cavities restoration, like zinc phosphate and silicophosphate cement. Yet some studies have shown that bacteria and microleakage might be involved in the “chemical toxicity” of these cement and other metallic materials (94–97).

The pulp responds to these irritations in varied and unpredicted ways, all inflammatory in essence. They can range from mild reversible inflammation to necrosis, including the allocation of tertiary dentin, depending on the intensity and duration of the injury and the ability of the pulp to recover. It typically begins with neutrophils infiltration into the pulp around the affected dentin. However, neutrophils can cause irreversible tissue damage while preventing the infection and damage from advancing. The inflammation and necrosis happen gradually, as explained by Langeland. Despite the initial spot of necrosis in the pulp horn and inflammation in the coronal part, the pulp in the canals did not show any sign of inflammation or necrosis (22,98).

3 PROPOSITION

This study aims to assess the use of tooth temperature measurement in determining pulp vitality for endodontic diagnosis through a systematic review of the literature and meta-analysis.

4 METHODS

4.1 Inclusion and Exclusion Criteria

The inclusion criteria were as follows:

1. An in-vivo study.
2. A human study.
3. Subjects of all sexes and ages.
4. Subjects have vital and nonvital teeth.
5. The study provides the equipment used.
6. Specifies if the teeth were normal, necrotic, or endodontically treated.
7. All languages.

The exclusion criteria were as follows:

1. An in-vitro study.
2. An animal study.
3. The study does not provide the equipment used.
4. Does not specify the condition of the examined teeth.
5. A review article.

4.2 Search Strategy

The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) checklist was adopted to conduct this systematic review, and it employed the (PICO) framework to address the study's objective; where the Population is patients with vital and nonvital teeth, the Intervention is measuring the tooth temperature or the time-temperature relationship, the Comparison is between vital and nonvital teeth groups, and the Outcomes are the differences between the groups.

The protocol was submitted to PROSPERO on May 30, 2022, ID 329692, but was rejected without revision since it did not match the admission criteria, which focused on COVID-19 during the 2020 pandemic. The study protocol was registered then on OSF on June 14, 2022, https://doi.org/10.17605/OSF.IO/7XT6Q. However, some information about the study, such as the title, was modified later.

Ten electronic databases (Cochrane, Bireme, PubMed, Web of Science, Scopus, SciELO, ClinicalTrials, Open Access Theses and Dissertations, OpenGrey, Embase) were searched from all the years, since there isn't any systematic review about the subject. The two keywords used were "diagnosis" and "tooth temperature." The search was narrowed down to the condition of "pulp necrosis" in the ClinicalTrials database and excluded “review” and “in vitro” in Scopus database. For all other databases, all of the results were examined without narrowing.

The search equations are presented in the following Figure 4.1.

Figure 4.1 – Search equations separated by database

Data Base	**Search Equation**
Cochrane	Diagnosis in Title Abstract Keyword AND tooth temperature in Title Abstract Keyword
Bireme	diagnosis AND tooth temperature
PubMed	("diagnosable"[All Fields] OR "diagnosi"[All Fields] OR "diagnosis"[MeSH Terms] OR "diagnosis"[All Fields] OR "diagnose"[All Fields] OR "diagnosed"[All Fields] OR "diagnoses"[All Fields] OR "diagnosing"[All Fields] OR "diagnosis"[MeSH Subheading]) AND (("teeth s"[All Fields] OR "teeths"[All Fields] OR "tooth"[MeSH Terms] OR "tooth"[All Fields] OR "teeth"[All Fields] OR "tooth s"[All Fields] OR "tooths"[All Fields]) AND ("temperature"[MeSH Terms] OR "temperature"[All Fields] OR "temperatures"[All Fields] OR "temperature s"[All Fields]))
Web of Science	diagnosis (All Fields) and tooth temperature (All Fields)
Scopus	(TITLE-ABS-KEY (diagnosis) AND TITLE-ABS-KEY (tooth AND temperature) AND NOT TITLE-ABS-KEY (review) AND NOT TITLE-ABS-KEY (in AND vitro))
SciELO	(diagnosis) AND (tooth temperature)
ClinicalTrials	diagnosis and tooth temperature | Pulp Necrosis
Open Access Theses and Dissertations	diagnosis in All of these words AND tooth temperature in All of these words
OpenGrey	diagnosis AND tooth temperature
Embase	tooth AND temperature AND diagnosis

Source: The author.

4.3 Study Selection

One researcher retrieved the records from the electronic databases. Further studies were added manually by reviewing the references of a couple of articles. All of the data was added to Rayyan for the process (99) . The articles were then screened and selected by two researchers based on the title and abstract, followed by the complete content search according to the inclusion and exclusion criteria. Throughout the process, both researchers were blind to each other's decisions. They resolved any conflict regarding inclusion through discussions and collective decisions at the end of the selecting phase.

Many institutions and libraries were contacted to inquire about the availability of some papers whose contents were unavailable online. If the publications were accessible, they were forwarded or manually scanned and emailed to one of the researchers. Following the above process, a few papers were still unavailable. Such questionable paper for inclusion was written by Mauser and Egg (100) ; attempts to obtain the paper were made directly to the university, journal, and professors without success.

4.4 Data Extraction

The researchers completed a test evaluation for the papers that presented inclusion criteria. One of them extracted the data and mounted it on a Microsoft Excel sheet (101) . The sheet included the author's name, year of publication, number of patients, patient age, room temperature, examined teeth type, sample size, type of isolation, the method used, results, nonvital tooth type, mean of temperatures and standard deviation for vital and nonvital teeth. The other researcher checked and verified all the extracted data.

The outcomes assessed in the systematic review were the significant differences in base temperatures and in the time-temperature relationship for both vital and nonvital teeth in the studies.

4.5 Risk of Bias Assessment

Two reviewers assessed the quality of the studies and completed the critical assessment file using a Joanna Briggs Institute Prevalence Critical Appraisal Checklist (102,103). The checklist for diagnostic test accuracy studies aims to analyze the methodological quality of the research and address the possibility of bias in their structure. The assessment findings were recorded initially on two separate Microsoft Excel sheets before being compiled in one table using the same program (101). In addition, a funnel plot analysis was applied to assess publication bias of each study.

4.6 Data Synthesis

RStudio using 'meta' package (v4.17-0) was utilized to conduct the meta-analysis (104), using the standardized mean difference as the outcome measure. The means and standard deviations of vital and nonvital teeth temperatures were obtained from the studies. When the data was unavailable, attempts to contact the authors were made to acquire the missing data. When there was data in the investigations but without the needed values, manual calculations as shown in Appendix (A) were performed in another excel sheet to include the individual base temperatures of each vital and nonvital tooth and obtain the means and standard deviations.

In the study of Banes and Hammond, only teeth without crowns were included in the data extraction and tests (58).

In Brown and Goldberg's investigation, both lingual and buccal surfaces were examined, and only the buccal surface measurements were considered for the meta-analysis (54).

The teeth that did not respond to the electric pulp tests in Crandell's article were regarded as nonvital in the analysis (69).

Howell et al. (64) employed a thermocouple and a thermistor for temperature calibration with the colors of the liquid crystals. The thermistor calibration method was selected for the analysis. The yellow-red was considered orange at 32°C. Red-green was deemed yellow at 33°C. 35.5°C was assigned to the dark green. The blue-green temperature was considered 36°C.

Hartley et al. (70) measurements included teeth with crowns. However, since the readings of crowned teeth seemed inconsistent in the literature, we omitted all crowned teeth from the statistical tests and meta-analysis.

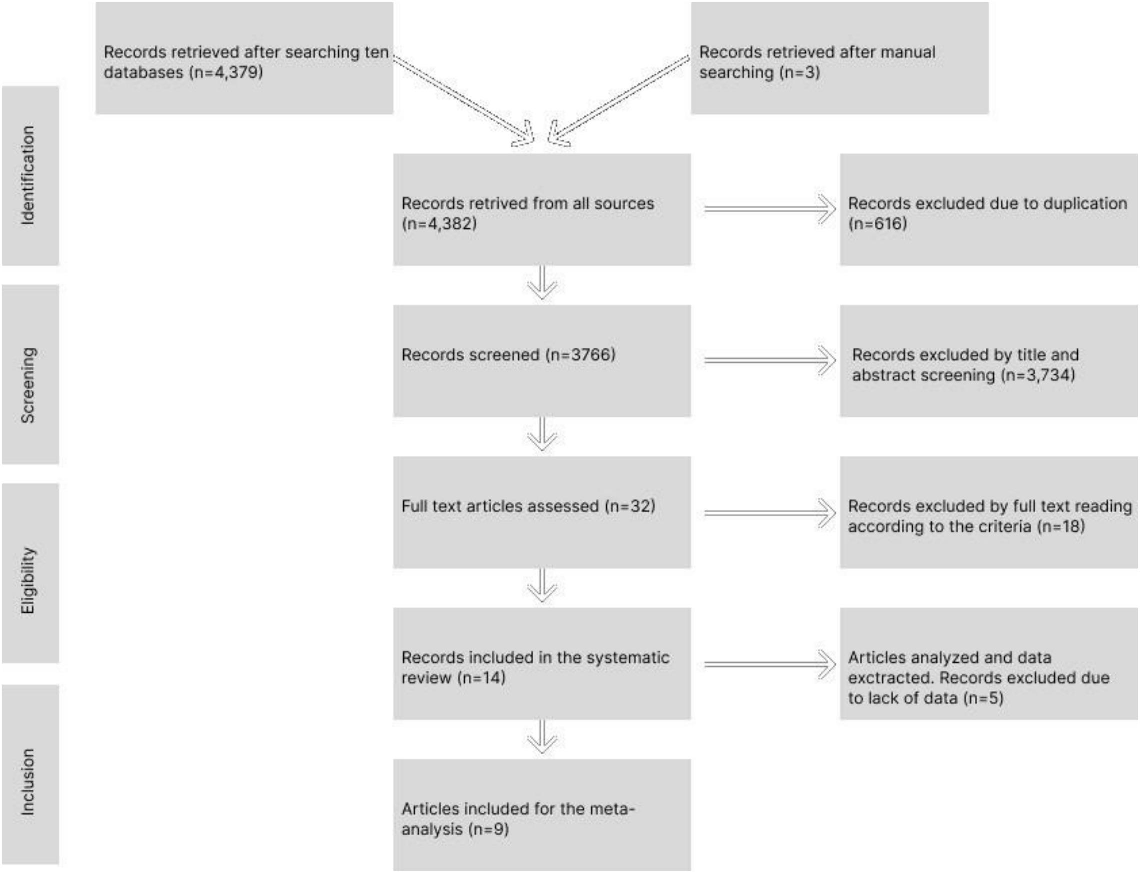
Five of the publications included in the systematic review were excluded from the meta-analysis. That was due to the lack of base temperatures of the examined teeth and the inability to obtain such data from the authors (59,71,105–107).

A test for the heterogeneity of the studies was performed. Finally, a forest plot was implemented to highlight the comparisons.

5 RESULTS

The electronic database searches yielded 4379 articles. The authors additionally included three papers discovered manually in the references of other publications, as shown in Figure 5.1 and Figure 5.2. Rayyan acquired 4382 new articles (99) , with 616 duplicates identified and eliminated. The titles and abstracts of 3766 publications were evaluated, and 3734 were excluded. A thorough analysis of 32 publications was performed, and 18 articles were eliminated based on the criteria.

Figure 5.1 – Flow diagram of the selected studies



Source: The author.

Figure 5.2 – Search results separated by database

Data Base	Number of Results
Cochrane	61
Bireme	261
PubMed	1795
Web of Science	96
Scopus	260
SciELO	2
ClinicalTrials	1
Open Access Theses and Dissertations	1525
OpenGrey	12
Embase	366

Source: The author.

Komoriyama et al. (68) published one study on the utility of thermography in the dental area. Despite using the approach to measure the temperatures of intraoral structures, particularly the posterior region, the study did not compare vital and nonvital teeth temperatures. As a result, it was excluded from the review.

Kells et al. (108) conducted another study on thermography that was excluded from this review. The researchers analyzed the temperatures of the gingival and incisal portions of the teeth in-vivo. They utilized a rubber dam to isolate the teeth, and an infrared thermal system was applied to scan them. The authors observed a temperature gradient from gingival to incisal sections of all the teeth, with no variation between the right and left pairs. However, all the teeth were sound and responded positively to the electric pulp test. Therefore, there was no comparison between vital and nonvital teeth.

According to some authors, the surface temperatures of vital and non-vital teeth were not significantly different.

Since Brown and Goldberg could not establish a link between vitality and tooth temperature when examining isolated superior anterior teeth under controlled conditions, the authors proposed that periodontal tissue is the primary source of the tooth's heat. Additionally, it was observed that the palatal faces were warmer than the buccal surfaces (54).

In an experimental investigation, Crandell and Hill included a patient with a known periapical abscess. The study concluded that thermography has only limited applications in dentistry since it could not find a relationship between the findings of the electric pulp testing and the temperatures of the teeth (69).

Howell et al. (64) conducted another study on the vitality of teeth in which they measured the temperatures of both vital and non-vital teeth using liquid crystal thermography. The measurements of a part of the non-vital teeth were lower than that of the control group. The other part had similar or higher readings.

Hartley et al. (70) concluded in another early experimental study that there is no thermal difference between vital and endodontically treated teeth and that the heat that the tooth loses is conducted primarily from the supporting tissues because the pulp's contribution to the tooth temperature is insignificant. Despite being unexpected, the temperature of the tooth with the root canal obturation was slightly higher than that of the vital tooth. It was unsuccessful in identifying an appropriate connection between dental temperature and pathology.

On the other hand, other researchers discovered that the temperatures of teeth with nonvital pulp are lower than those of teeth with vital pulp.

Mendes et al. (72) proved that different states of the pulp might have varying temperatures in another investigation examining the viability of anterior teeth. The research revealed a significant difference between endodontically treated teeth when compared to both vital and necrotic ones. However, there was no correlation or significant difference between necrosis and vitality.

Banes and Hammond found that nonvital teeth had lower temperatures than the vital ones when not covered by full coverage crowns. They subjected 84 teeth to surface temperature examination; half had undergone endodontic treatment and had vital contralateral counterparts (58).

In a different study by Stoops and Scott, they selected 23 patients with pulpless teeth that required endodontic therapy in addition to vital, asymptomatic contralateral teeth. The range of temperature differences between the subjects under investigation was 0.13 to 0.75 °C, with a mean of 0.55 °C. The authors concluded that there is a relationship between the tooth's vitality and temperature, which may be helpful for diagnosis (61).

Numerous other authors have investigated the time-temperature relationship in vital and nonvital teeth and found it efficient in determining pulp vitality. That entails warming or cooling the teeth to a specific temperature before comparing how the two actions differ.

Fanibunda conducted two of the most significant investigations into tooth temperature. He divided the first study into three stages and examined the relationship between time and temperature during the second. The measurements included 32 nonvital and 41 vital maxillary anterior teeth. The patients were instructed to keep their mouths closed until they reached a stable state. Opening the mouth and a rapid drop in temperature, known as a cooling period, followed. The starting temperatures of all teeth in the steady state did not differ significantly, according to the author. They observed that the temperature did rise in the teeth known to be vital after the cooling period, but not in the nonvital teeth (105).

Fanibunda's second clinical evaluation of tooth temperature included 94 recordings of vital, nonvital, and reimplanted teeth. After stabilizing the patients and reaching a steady condition at zero level, a rubber polishing cup attached to a handpiece stimulated the crowns for 12 seconds. The temperature recording continued for 2 minutes and 40 seconds after the stimulation period, except for certain teeth that did not reach a stable condition during this specific time. A steady state was defined as a temperature that remained constant for 30 seconds, which was proceeded by a critical period. It was observed that the nonvital teeth took shorter time to cool down and reach a steady state than vital teeth, which had longer critical periods. Based on these findings and discrepancies, the author concluded that the time-temperature relationship is effective for pulp vitality (59).

Pogrel et al. (71) investigated 20 volunteers with vital, necrotic, and endodontically treated teeth in another study that used infrared thermography to measure tooth temperatures. Some conditions, such as the rubber dam and controlled room temperature, were set up to achieve consistent results. It was observed that all teeth exhibited the same temperature gradient from gingival to incisal, vital and nonvital alike. However, after being cooled by a stream of cold air, vital teeth rewarmed in 5 seconds, but nonvital teeth took up to 15 seconds.

In a more recent paper, Kamath and Nasim evaluated 75 people who had a single-rooted anterior tooth that needed endodontic treatment. The baseline temperatures were taken for all individuals, and the mean average was similar in both vital and nonvital teeth with no significant difference. The pattern of the rewarming profile between both groups was not statistically significant after cooling the teeth with a cold stimulus to evaluate the time-temperature relationship. However, it is crucial to note that vital teeth could recover to their baseline temperature in 3 minutes while none of the nonvital teeth could.

Despite these findings, the authors suggested the method's reliability for diagnostic procedures (73).

On the contrary, multiple researchers analyzing the time-temperature relationship found it ineffective for detecting pulp conditions and pathologies.

Kells et al. (107) employed thermographic imaging to measure the surface temperatures of teeth and the time-temperature relationship. After verifying the suitability of the two cold stimuli, ice sticks, and cold airstream, in vitro, one patient was recruited for the experiment in vivo. The patient had one endodontically treated central incisor and a vital contralateral that were checked by cooling and recording temperature measurements. After five days, the complete process was repeated for both the stimuli and the teeth. The rewarming rate for vital and nonvital teeth was similar. According to the authors, pulpal flow has no role in rewarming after a cold stimulation. Furthermore, because gingival sites rewarmed faster than incisal sites, it was determined that the surrounding tissues play a more crucial role in the rewarming process. However, it is essential to note that these results are based on examining one subject.

Elias experimented with assessing the vitality of the teeth by measuring their temperatures. After applying a rubber dam to isolate the teeth, the measurements were recorded in a controlled setting. The teeth were then cooled to evaluate the time-temperature relationship of the teeth. The authors found no significant difference between vital and nonvital teeth for both base temperatures and the time-temperature relationship. In addition, the study found that using a rubber dam was considered unnecessary if the ambient is controlled and stable (106).

Smith et al. (60) evaluated the time-temperature relationship on ten individuals' anterior maxillary teeth, most of which were central incisors for easier access and reproducibility. The initial temperature of the tooth was measured, followed by a cold stimulus and a spray of air. Following that, a 4-minute recovery time was on the observation. The authors compared the recovery patterns and initial temperatures of vital and nonvital teeth and discovered that none of the comparisons were statistically significant. They concluded that measuring the surface temperature cannot be a reliable nor predicted method to estimate pulp vitality.

Figure 5.3 shows the critical evaluation of the research included using the Joanna Briggs Institute Checklist. The assessment shows that patient selection was not ideal in most of the included investigations, with only six studies enrolling a consecutive or random sample of patients. Likewise, the pulp vitality condition was known to the authors through various other methods, that means many papers used a case-control approach. Another factor is that most of the studies were evaluated probably by the same person who was not blind to the tests and results. The investigations yielded largely positive outcomes in the other domains. Furthermore, the funnel plot is shown in Figure 5.4. The rank correlation and regression tests both showed no funnel plot asymmetry ($p = 0.1194$ and $p = 0.2398$, respectively).

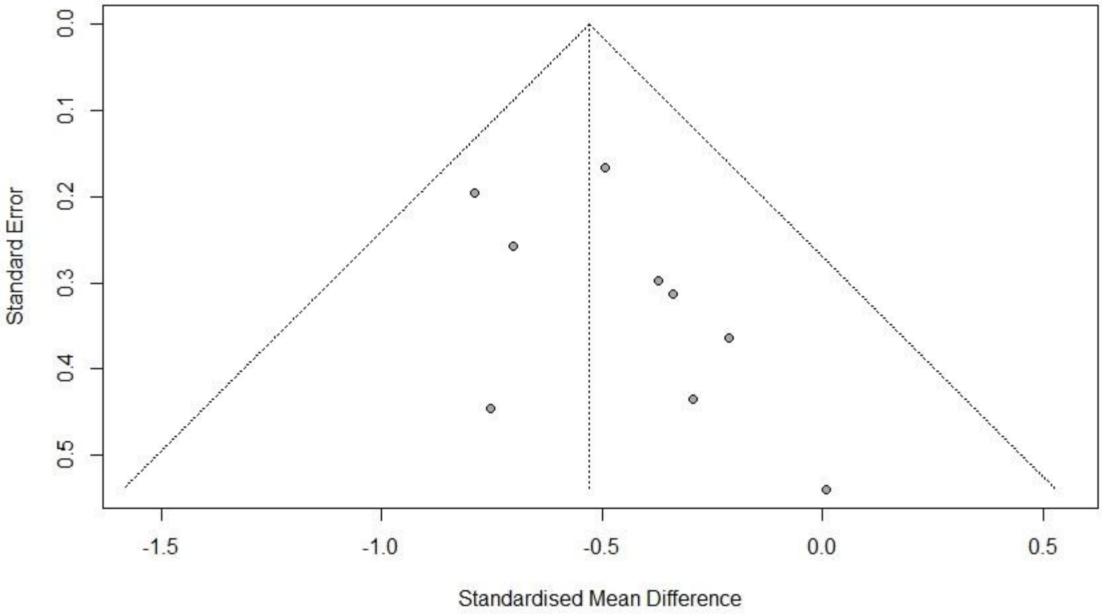
Figure 5.3 – Risk of Bias of the Included Studies

Studies	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10
Banes et al. 1978	U	No	Yes	No	NA	Yes	No	Yes	Yes	Yes
Brown et al. 1966	Yes	No	Yes	No	NA	Yes	No	Yes	No	Yes
Crandell et al. 1966	No	No	U	No	NA	Yes	No	Yes	Yes	Yes
Fanibunda a, 1986	Yes	Yes	Yes	No	No	Yes	No	Yes	No	Yes
Fanibunda b, 1986	Yes	Yes	Yes	No	No	Yes	No	Yes	No	Yes
Howell et al. 1970	No	Yes	Yes	Yes	NA	Yes	Yes	Yes	Yes	Yes
Kamath et al. 2020	Yes	No	Yes	No	Yes	Yes	No	Yes	Yes	Yes
Elias, 2008	No	No	Yes	No	Yes	Yes	No	Yes	Yes	Yes
Kells et al. 2000	No	No	Yes	No	Yes	Yes	No	Yes	Yes	Yes
Mendes et al. 2020	Yes	No	Yes	No	NA	Yes	No	Yes	Yes	Yes
Pogrel et al. 1989	U	No	U	No	No	Yes	No	Yes	Yes	Yes
Smith et al. 2004	Yes	Yes	Yes	No	Yes	Yes	No	Yes	No	Yes
Stoops et al. 1976	No	Yes	Yes	No	NA	Yes	No	Yes	No	Yes
Hartley et al. 1967	No	No	U	No	NA	Yes	No	Yes	No	Yes

* Joanna Briggs Institute Critical Appraisal Checklist For Diagnostic Test Accuracy Studies, enrolling consecutive or random sample of patients (Q1); avoiding case-control study (Q2); avoiding inappropriate exclusions (Q3); interpreting index test results without knowledge of the results of the reference standard (Q4); Pre-specifying a threshold, if it is used (Q5); the likelihood of correctly classifying the target condition by the reference standard (Q6); interpreting the reference standard results without knowledge of the results of the index test (Q7); an appropriate interval between index test and reference standard (Q8); all patients receiving the same reference standard (Q9); including all patients in the analysis (Q10); U: Unclear; NA: Not Applicable

Source: The author.

Figure 5.4 – Funnel Plot



Source: The author.

A full summary of the final studies chosen is provided in Figure 5.5. Due to a lack of randomized controlled trials, the systematic review relied on observational studies.

Figure 5.5 – The extracted data from the included papers

Author	Number of Patients	Tooth Type	Sample Size
Banes et al. 1978	35	Various Teeth	42 V - 42 NV
Brown et al. 1966	14	Upper Canine to Canine	72 V - 12 NV
Crandell et al. 1966	4	Upper Canine to Canine	16 V - 8 NV
Fanibunda a, 1986	21	Maxillary Anterior Teeth	41 V - 23 NV
Fanibunda b, 1986	48	Various Teeth	33 V - 43 NV - 18 transplanted and implanted
Howell et al. 1970	8	Anterior Teeth	12 V - 10 NV
Kamath et al. 2020	75	Anterior Teeth	75 V - 75 NV
Elias, 2008	4	Anterior Teeth	4 V - 2 NV
Kells et al. 2000	1	Upper incisors	1 V - 1 NV
Mendes et al. 2020	58	Anterior Teeth	153 V - 33 NV (60 V control)
Pogrel et al. 1989	20	Anterior Teeth	20 V - 5 NV
Smith et al. 2004	10	Upper incisors	11 V - 5 NV
Stoops et al. 1976	23	Various teeth	23 V - 23 NV
Hartley et al. 1967	15	Various Teeth	147 V - 8 NV

to be continued

continuation

Isolation	Method	Results
Dried with Gauze - Rubber dam when full gold crown	Thermistor	Significant difference when not covered by a gold crown
Rubber Dam	Thermocouple	No significant difference
No isolation	Infrared thermometer - thermograph	No significant difference
Dried with Gauze	Electric Thermometer	No significant difference
Dried with Gauze	Thermistor	/
Rubber Dam or Cotton Rolls	Cholesteric liquid crystals	No significant difference
Rubber Dam	Laser guided Infrared Thermometer	No significant difference
Rubber Dam	Infrared Camera	No significant difference
Rubber Dam	Infrared Camera	/
Relative Isolation	Infrared Camera	Significant difference between Vital and Endo but not with Necrotic
Rubber Dam	Infrared Camera	No significant difference
Dried with Gauze - Cotton Rolls	Thermometers / Thermistor	No significant difference
Air - Cotton Rolls	Thermistor	Significant difference
Dried	Infrared Thermometer / Camera	No significant difference

to be continued

continuation

Time-Temperature Relationship	Nonvital Teeth
/	Endo Treated
/	Endo Treated
/	Necrotic
A rise of temperature after cooling period in vital teeth, not present in non-vital	Necrotic
Vital teeth took longer time to cool down than non-vital teeth	Endo Treated - Necrotic
/	Necrotic
No significant difference	Necrotic
No significant difference	Endo Treated
No significant difference	Endo Treated
/	Endo Treated
/	Necrotic
Vital teeth rewarmed faster than non vital teeth	Endo Treated - Necrotic
No significant difference	3 Endo Treated, 1 sclerosed, 1 Necrotic
/	Necrotic
/	Endo Treated - Necrotic

to be continued

conclusion

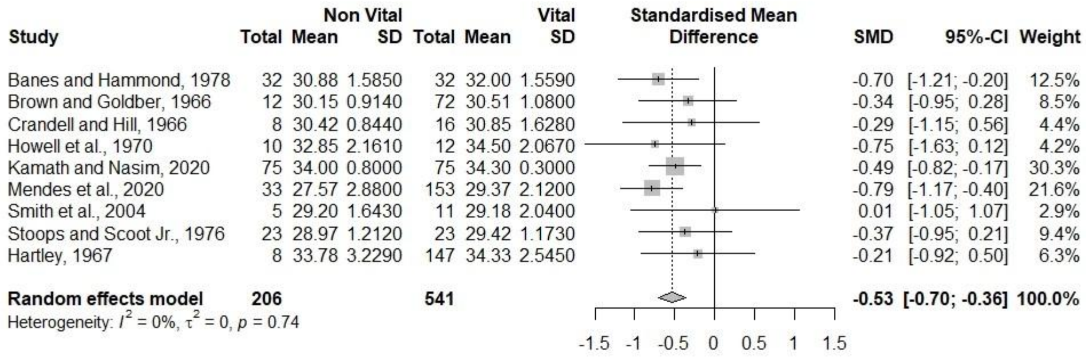
M. Vital	S.D. Vital	M. Nonvital	S.D. Nonvital
31,997	1,559	30,881	1,585
30,511	1,08	30,15	0,914
30,851	1,628	30,416	0,844
/	/	/	/
/	/	/	/
34,5	2,067	32,85	2,161
34,3	0,3	34	0,8
/	/	/	/
/	/	/	/
29.37	2.12	27,57	2,88
/	/	31,33	2
/	/	/	/
29,182	2,04	29,2	1,643
29,418	1,173	28,968	1,212
34,333	2,545	33,785	3,229

* V: Vital teeth; NV: Nonvital teeth; M: Mean; S.D: Standard deviation

Source: The author.

The meta-analysis comprised k=9 studies. There were 206 nonvital and 541 vital teeth in the samples, with a mean temperature of 30.87 ° C for nonvital and 31.6 ° C for vital teeth. Based on the random-effects model, the estimated average standardized mean difference was -0.53. As a result, the average outcome deviated considerably from zero as shown in the forest plot Figure 5.6.

Figure 5.6 – Forest Plot



Study	Non Vital Total	Non Vital Mean	Non Vital SD	Vital Total	Vital Mean	Vital SD	SMD	95%-CI	Weight
Banes and Hammond, 1978	32	30.88	1.5850	32	32.00	1.5590	-0.70	[-1.21; -0.20]	12.5%
Brown and Goldber, 1966	12	30.15	0.9140	72	30.51	1.0800	-0.34	[-0.95; 0.28]	8.5%
Crandell and Hill, 1966	8	30.42	0.8440	16	30.85	1.6280	-0.29	[-1.15; 0.56]	4.4%
Howell et al., 1970	10	32.85	2.1610	12	34.50	2.0670	-0.75	[-1.63; 0.12]	4.2%
Kamath and Nasim, 2020	75	34.00	0.8000	75	34.30	0.3000	-0.49	[-0.82; -0.17]	30.3%
Mendes et al., 2020	33	27.57	2.8800	153	29.37	2.1200	-0.79	[-1.17; -0.40]	21.6%
Smith et al., 2004	5	29.20	1.6430	11	29.18	2.0400	0.01	[-1.05; 1.07]	2.9%
Stoops and Scoot Jr., 1976	23	28.97	1.2120	23	29.42	1.1730	-0.37	[-0.95; 0.21]	9.4%
Hartley, 1967	8	33.78	3.2290	147	34.33	2.5450	-0.21	[-0.92; 0.50]	6.3%
Random effects model	**206**			**541**			**-0.53**	**[-0.70; -0.36]**	**100.0%**

Heterogeneity: $I^2 = 0\%$, $\tau^2 = 0$, $p = 0.74$

Source: The author.

While there was a significant difference in three of the nine investigations included in the meta-analysis, the 95% confidence intervals for six of the nine studies overlapped zero, indicating no statistical difference. Furthermore, the overall 95% confidence interval does not overlap zero, suggesting that not all studies have statistical significance at the study level, whereas there is statistical significance at the meta-analysis level.

The analysis, however, discovered no heterogeneity in the sample (p=0.74). Moreover, there were no outliers in the context of the model. The three studies with significant differences obtained the most weight in the analysis (58,72,73).

6 DISCUSSION

This systematic review aimed to examine the evidence for diagnosing pulp vitality by assessing tooth temperature. The demand for a systematic review on the subject was motivated by the conflicting findings in the literature. To our knowledge, there are no systematic reviews or meta-analyses on this issue.

Jafarzadeh et al. (109) investigated inspecting tooth temperature for endodontic diagnosis in a literature review. The authors examined the equipment used for the test, the associated factors, and the test's efficacy. Because of the procedure requirements, it was concluded at the time that the method was unfeasible for routine application in clinical endodontics. However, as technology advances, it may become more crucial in the future.

Unlike other vitality tests, measuring tooth temperature should be done in a fully controlled environment because the surface temperature is not a fixed value and fluctuates correspondingly to internal and external factors (110). As a result, regulating as many variables as possible will probably produce the most precise readings.

On the one hand, if the pulpal blood flow contributes to tooth temperature while also providing nutrition to the peripheral tissue (111), we can assume that any changes to this microcirculation can modify this contribution. For example, when investigating pulpal blood flow in dogs, they observed that experiments involving younger canines yielded higher values than older ones (41,112) . That means the blood flow might be different in younger patients, which can cause them to have higher temperatures. Additionally, studies have shown that the prevalence of pulp calcification increases with age (113,114). As a result, this can cause a decreased pulpal blood flow, in other words, lower temperatures. However, this was not observed or analyzed in any studies included in this review. The ages of the examined patients ranged from 11 to 65 years old (54,59,60,72,73,106,107).

Moreover, pulpal tissue can resist the damage in inflammation by releasing chemical mediators and other vasoactive molecules in a reactive process triggered by the injured cells. As a result, pulpal blood flow increases in proportion to the severity of inflammation. When pulp inflammation was established experimentally in dogs, blood flow rose by 35% compared to the control sample after three days of inflammation (75). We can presume from this data that teeth with different endodontic conditions may have varying temperatures. None of the studies included in the review looked at the temperatures of teeth with inflamed pulp, whether it was reversible or irreversible. In one study, they examined the application of thermography in the diagnosis of periapical inflammatory lesions. After comparing the temperatures of acute pulpitis with apical periodontitis, acute periapical abscess, and chronic periapical abscess in a total of 80 patients, the difference between the groups was significant, with acute periapical abscess having the highest mean temperature. However, the groups were not compared to nonvital teeth (115).

As a result, heat generated by the pulp flows through the mineralized material of the tooth to reach the surface. Hence, tooth architecture is significant in heat transmission. Dentin is a heterogeneous composite material composed of micrometer-sized tubules surrounded by peritubular dentin embedded inside a collagen matrix (116). Many investigations have demonstrated that these tubules have a conical shape and that their number and radius increase as they come closer to the pulp chamber. As a result, heat is transferred more effectively into the pulp (117,118). This structure may make it more difficult to transmit heat in the other way, from the pulp to the surface.

The heat would then move through the dentin-enamel junction, which was found to slow down heat transfer in low temperatures by storing heat. This mechanism is thought to protect the dental pulp from damage and might affect heat transmitting from the pulp (119).

Furthermore, the enamel has a distinct structure of rods that run almost perpendicular from the dentin-enamel junction to the tooth surface (120). When heat is applied to sound teeth, one of the most significant variations in thermal response between enamel and dentin is that enamel transmits heat faster than dentin due to its higher mineral content, which provides higher thermal conductivity (121). Likewise, when discussing heat transmission, the thickness of these layers is considered since prepared teeth with a small quantity of residual dentin thickness were more prone to temperature increase (122).

On the other hand, many studies have kept the room temperature between 20 °C and 24 °C, with a steady humidity level (54,69,71–73,106,108). It should be free of sunlight (69) and wind (68), and the dental lamp should be inoperative to avoid radiation and heat interference (105). Patients were asked not to eat, drink, or smoke for at least one hour before the exam (106,108). Another study suggests stopping smoking for at least four hours to avoid elevating the oral cavity temperature (68). The authors gave the patients 10 to 20 minutes to relax and stabilize (69,108) by lying down or supporting their heads (72). In one study, they constructed a specific fixed platform to back the head and chin (106). The patients were also instructed not to breathe through their mouths (68,71).

Evaporation from wet surfaces is thought to interfere with accurate readings, as observed in one study while measuring the temperature of the skin surface, with a higher rate from warmer places (123). However, one study discovered no variation in readings between wet and dry teeth, although they dried the teeth as a precaution for consistency (70). As a result, numerous studies have used cotton gauze (54,58–60) or air to dry the teeth before examinations. Stoops discovered that the temperature measuring equipment is so sensitive that a modest amount of saliva or a disturbance in the local air in the room could impact the results (61).

Furthermore, the application of a rubber dam was proposed for and utilized in various research to standardize the data and eliminate oral air streams (54,71,73,107). Kells et al. (107) improved the rubber dam to exclude nasal air currents as well. In another investigation (54), the authors placed an additional cotton pad between the lip and the interior side of the dam to limit heat transmission from the surrounding tissues to the inspected teeth. Even though one study discovered that breathing rhythms alter the outcomes (70), several studies solely implemented relative isolation using cotton rolls (60,61,72). Smith et al. (60) evaluated the effect of the presence and absence of a rubber dam in a pilot experiment and found no significant influence on the temperature stability. As a result, they did not use a rubber dam during the investigation. Elias took numerous temperature readings with and without a rubber dam for comparison and found no significant difference between the groups studied. For this reason, the authors determined that total isolation with a rubber dam is optional (106). Due to the difficulty with salivary control in the posterior oral region, another study proposed using a rubber dam when examining the posterior teeth only (72).

When a tooth, whether vital or nonvital, has a full cast crown, the surface temperature differs from natural teeth. Therefore, assessing the tooth temperature was noticed to be unreliable in the presence of crowns or extensive restorations. That can be explained by the effect of restorations on tooth heat transfer, as many studies demonstrated that the thermal performance of restored teeth differs considerably from that of sound teeth due to differences in the thermophysical properties of the dental materials and the teeth (124–126). Banes et al. (58) compared ten cases of teeth with a full cast crown placed on them or their contralateral teeth. He found no significant statistical difference between vital and nonvital ones, in contrast to the results obtained from natural teeth without crowns or restorations. That could be a critical disadvantage because the method of assessing the surface temperature is usually advocated when the electric pulp test fails, such as in full coverage crowns. In another study, heat was used to stimulate vital, nonvital, and reimplanted teeth with a rubber cup. Twelve nonvital teeth had prosthetic crowns with/or posts. Following stimulation, the temperature rose to a peak before returning slowly to a stable condition. The critical period is the time between the end of the stimulus and the steady state. It ranged longer in nonvital teeth with crowns than in those without them, which made their readings inaccurate as they showed vital-like behavior (59). The teeth base temperatures were measured in a different investigation before being cooled with a stream of cold air to evaluate the rewarming behavior of vital and nonvital teeth. One unexpected outcome of a nonvital tooth with a metallic post put into the apex because it rewarmed faster than vital and nonvital teeth. It was attributed to the metal's temperature conductivity which is faster than natural teeth's blood supply (71). When analyzing the temperatures of only vital teeth in the first stage of his experiment, Fanibunda excluded crowned teeth entirely (105) . Some authors did not include any tooth with crown or restoration (60,61,72) . Moreover, others have acknowledged that one of the downsides of this procedure is evaluating teeth with crowns and restorations (73).

Furthermore, many studies resulted in contradictory values, such as nonvital teeth being warmer than vital teeth, which was not predicted by the authors (54,69) . Hartley et al. (70) observed that the normal tooth is 1.77 °C colder than the endodontically treated tooth in the patient tested when attempting to achieve the most accurate measurements with an infrared camera. That was present even in the studies that showed a significant difference between vital and nonvital teeth (58). Additionally, when the authors opened the canals of a group of these pulpless teeth for treatment, they hemorrhaged and were discovered to have pulp-like tissue. Besides that, two of the patients reported pain during the instrumentation. This granulation-like tissue was thought to affect the vascularity and temperature of the tooth (61,64).

There are multiple limitations associated with the type and shape of teeth evaluated by measuring their temperatures. Many studies (54,69,71,105,107) only included anterior maxillary teeth in the sample to facilitate access, repeatability, and convenience (60), although others also included anterior mandibular teeth (64). Besides, different authors have attempted to incorporate in the measurements a broader range of teeth, such as premolars and molars from both arches (58,59,61,70). This emphasis on anterior teeth may imply that adopting the technology for assessing posterior teeth, particularly with infrared thermography, is complicated or inadequate. According to one study (72), infrared thermography has some difficulties evaluating crowded and inclined teeth. Furthermore, they suggested performing the procedures on the occlusal or palatine side for posterior teeth because performing on the buccal face is challenging. Moreover, another study (68) proposed using the same technique on a dental mirror that reflects the oral components indirectly, although they could not reach the third molar following this procedure. A different paper (73) noted that measuring tooth temperature could be complicated when assessing multirooted teeth with infrared thermography. That could be related to their posterior position and the nature of pulpal pathology, which can progress in one root while remaining vital in the other.

This study, however, has several limitations. First, the device or equipment utilized for the procedure, the environmental conditions, the age group of the patients, the type of examined teeth, the type of nonvital teeth, and the type of isolation all differed in the included studies, resulting in many varied factors. That might have affected the outcomes since the methodology was not the same. Furthermore, the risk of bias was not excellent for most of the publications, which might affect the reliability of the current results.

Accordingly, this study's findings indicate a significant difference in the temperatures of vital and nonvital teeth. These findings imply the need for developing the ideal approach to adopt this method in clinical practice. The approach can be advantageous for endodontic diagnosis when x-rays ought to be minimized, such as in children and pregnant women (127). Besides this, it can help in cases of trauma where the teeth are still vital but do not respond to conventional vitality tests like cold and electric testing (128) . Thus, future research should focus on more randomized trials rather than observational ones, with a randomized sample of patients and blinded results evaluation. Due to the lack of data in the literature, addressing teeth with crowns in further research and including more posterior teeth in the sample is recommended. Similarly, we suggest investigating the temperatures of different pulp pathological conditions and cases of trauma.

7 CONCLUSIONS

In clinical settings, teeth with different pulp states may present at different temperatures. Within the limits of this systematic review and meta-analysis, the results demonstrate that measuring tooth temperature may be an asset in the endodontic diagnosis of tooth vitality. However, further research with high-quality studies is required to validate these findings.

8 DECLARATION OF CONFLICTING INTERESTS

The authors declare that they do not have any known conflicting interests that could have influenced any step of the work described in this study.

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Appendix A – The individual measurements of some articles

	V	NV	A.V.	A.NV	S.D.V	S.D.NV
Banes	33,2	31,2	31,997	30,881	1,559	1,585
	30,9	30,2				
	31,8	30,8				
	34,9	33,4				
	33,8	33,1				
	34,2	32,6				
	31,8	30,6				
	30,8	29,4				
	31,8	31,7				
	32,4	30,9				
	34,9	33,1				
	33,4	32,5				
	32,4	32,8				
	32,7	30,7				
	31,1	30,6				
	33,8	32,8				
	30,7	27,8				
	31,7	30,2				
	31,4	30,5				
	30,1	29,5				
	29,8	29,9				
	29,1	28,8				
	32,7	31,2				
	33,8	32,6				
	33,1	32,4				
	32,7	32,3				
	32	28,3				
	31,2	29,5				
	29,8	29,5				

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	32,2	31,8				
	29,5	28,9				
	30,2	28,6				
Brown	29,5	30,6	30,511	30,15	1,08	0,914
	31,9	28,6				
	30,4	29,3				
	28	29,4				
	30,1	30,7				
	31,2	29,1				
	31,9	31,7				
	31,7	29,8				
	30,5	30,4				
	30,3	30,3				
	30,7	30,9				
	31,9	31				
	30,1					
	29,3					
	31					
	30,5					
	30,9					
	27,7					
	29,2					
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	30,4					
Crandell	88	87	30,416	30,851	1,628	0,884
	88	87,5	87,531 F	86,813 F		
	87	87				
	87	88				
	88	87				
	86,5	85,5				
	87	85,5				
	89	87				
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	89,5					
	84,5					
	84,5					
	85,5					
Howell	35	31	34,5	32,85	2,067	2,161
	35	32				
	35	32				
	33	31				
	36	31				

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	31	31				
	36	33				
	30	35,5				
	35	36				
	36	36				
	36					
	36					
Smith	31	31	29,182	29,2	2,04	1,643
	31	30				
	31	30				
	31	28				
	30	27				
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	26					
Stoops	28,25	27,5	29,418	28,968	1,173	1,212
	31	30,5				
	29,25	28,25				
	27,25	27,5				
	30,5	30				
	28	27,87				
	28,25	27,5				
	29,25	28,75				
	29,25	28,5				
	30,5	31				
	29,5	30				
	28	27,5				
	30,5	30				
	30,62	30				

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	30,13	29,63				
	30,5	29,87				
	28,25	27,63				
	28,25	27,75				
	28,25	27,63				
	30,25	29,63				
	29	28,5				
	31	30,5				
	30,87	30,25				
Hartley	91	90,5	34,333	33.785	2,545	3,229
	91	92	93,799 F	92,813 F		
	88	98				
	85,5	93				
	85	97				
	87	93				
	90,5	89				
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* V: Vital teeth temperatures; NV: Nonvital teeth temperatures; M.V: Mean value of vital teeth temperatures; M. NV: Mean value of nonvital teeth temperatures; S.D. V: Standard deviation of vital teeth; S.D. NV: Standard deviation of nonvital teeth

Source: The author.