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Original Article

Use of Thermal Imaging for Detection of Early Pulpal Inflammation After Deep Caries

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ABSTRACT

Background: Early diagnosis of pulpal involvement in deep carious teeth remains challenging because conventional pulp sensibility tests primarily assess neural response rather than vascular or inflammatory change. Dynamic infrared thermal imaging may provide a non-invasive adjunct by recording post-stimulation temperature recovery patterns that reflect altered tooth thermal behavior. Objective: To evaluate whether thermal imaging demonstrates altered recovery patterns in permanent teeth with deep caries and whether these findings correspond with routine cold test and electric pulp test responses. Methods: This hospital-based diagnostic technology study included 46 patients with one deeply carious permanent tooth each. After clinical and radiographic assessment, baseline thermal images were recorded under standardized conditions, followed by controlled cold stimulation and serial thermal imaging to assess post-stimulation recovery. Where available, corresponding control teeth were compared. Cold testing and electric pulp testing were performed after thermal recording. Main variables included recovery time, temperature difference, cold-test response, and electric pulp test pattern. Results: Deep carious teeth showed longer mean thermal recovery time than control teeth, with recovery increasing from 11.2 seconds to 18.4 seconds. Mean temperature difference increased progressively across cold-test categories: 0.6°C in normal response, 1.1°C in exaggerated but non-lingering response, 1.8°C in lingering response, and 2.2°C in no response. Longer recovery time also showed a positive clinical pattern with higher electric pulp test readings. Conclusion: Dynamic thermal imaging demonstrated delayed recovery and greater thermal alteration in deep carious teeth, with changes increasing across abnormal pulp sensibility responses. Thermal imaging may serve as a rapid, painless, and non-invasive adjunct for early pulpal assessment in clinically uncertain deep caries cases. Keywords: Thermal imaging, deep caries, pulpal inflammation, pulp vitality, infrared thermography, cold test, electric pulp test, endodontic diagnosis.

INTRODUCTION

Deep dental caries remains a major clinical challenge because the treatment decision depends not only on the depth of the lesion but also on the biological condition of the pulp. In teeth where the carious lesion approaches the pulp, clinicians must determine whether the pulp is healthy, reversibly inflamed, irreversibly inflamed, or necrotic before selecting conservative restoration, selective caries removal, vital pulp therapy, or endodontic treatment (1). This decision is particularly difficult because early pulpal inflammation may occur before the patient develops spontaneous pain, lingering sensitivity, swelling, or radiographic evidence of periapical disease. As a result, the apparent clinical presentation may

underestimate the actual inflammatory or vascular status of the pulp, creating a diagnostic gap in the management of deep carious permanent teeth (2,3).

Conventional pulp assessment in routine dental practice relies mainly on sensibility tests such as cold testing, heat testing, and electric pulp testing. Although these methods are simple, inexpensive, and widely available, they primarily assess neural response rather than true pulp vitality. A tooth may respond to cold or electric stimulation even when vascular changes have already begun, while another tooth may show a reduced or absent response because of technical, patient-related, or neural factors rather than complete loss of vitality (4). This limitation is clinically important because the pulp is a vascular connective tissue, and its ability to remain vital depends more directly on blood flow than on sensory response alone. Previous evidence has shown that the diagnostic accuracy of commonly used pulp tests varies and that methods closer to vascular assessment, such as laser Doppler flowmetry and pulse oximetry, may provide more biologically meaningful information about pulpal status (5).

Despite their biological relevance, vascular-based diagnostic methods have not become routine in many general dental or hospital settings. Laser Doppler flowmetry and pulse oximetry may require specialized equipment, careful technique, and additional clinical time, limiting their practicality in busy or resource-constrained environments (6). This is especially relevant in settings where patients frequently present with advanced caries and clinicians must make rapid but careful decisions about whether a tooth can still be managed conservatively. Therefore, there is a need for a non-invasive, patient-friendly, repeatable, and clinically feasible adjunctive tool that can help identify early pulpal changes in deep carious teeth before advanced symptoms or irreversible changes become obvious.

Infrared thermal imaging offers a potential solution because it records surface temperature patterns without direct contact and may indirectly reflect changes in pulpal blood flow, inflammation, and heat exchange. In medical diagnostics, altered tissue temperature has long been associated with inflammatory and vascular changes. In dentistry, this principle is biologically plausible because pulpal circulation can influence how a tooth responds to thermal stimulation and how quickly it returns toward baseline temperature afterward. Dynamic thermal response, rather than a single static temperature reading, may therefore provide useful information about underlying pulpal status. Previous thermographic studies have suggested that temperature recovery after stimulation may help distinguish teeth with different vascular conditions and may also assist in identifying odontogenic infection-related temperature changes (7,8).

The clinical relevance of this approach is strengthened by current concepts in deep caries management. Contemporary endodontic and restorative practice increasingly emphasizes preservation of pulp vitality, selective caries removal, and biologically based treatment rather than routine aggressive removal of pulp tissue. Such conservative approaches are only appropriate when pulpal diagnosis is sufficiently accurate. If early reversible pulpal changes are overdiagnosed as irreversible disease, the patient may receive unnecessary endodontic treatment. Conversely, if advanced pulpal breakdown is underestimated, conservative treatment may fail. A diagnostic adjunct capable of detecting altered thermal behavior in deep carious teeth could therefore support more precise treatment planning and help preserve pulp vitality where recovery remains possible (9).

However, the existing evidence remains limited regarding the use of thermal imaging specifically in permanent teeth with deep caries before clear symptoms of advanced pulpal disease appear. Prior studies have explored thermography in relation to tooth vascularization, vital and non-vital teeth, and odontogenic infection, but fewer clinical studies have examined whether dynamic thermal recovery patterns correlate with conventional pulp test responses in early or doubtful pulpal conditions associated with deep carious lesions (10,11). This gap is important because the most difficult clinical decisions are often made at this early stage, when symptoms are mild, absent, or inconsistent with the depth of the lesion.

Based on this rationale, the present diagnostic technology study evaluated the use of infrared thermal imaging as an adjunctive method for assessing suspected early pulpal changes in permanent teeth with deep caries. Using a PICO framework, the population comprised patients with deep carious permanent teeth, the index assessment was dynamic thermal imaging after controlled stimulation, the comparator included contralateral control teeth and routine pulp sensibility tests, and the primary clinical outcome was altered thermal recovery behavior associated with abnormal pulp test responses. The objective was to determine whether deep carious teeth demonstrate delayed thermal recovery or greater temperature alteration compared with control teeth and whether these thermal parameters show a meaningful relationship with cold test and electric pulp test findings. This framing aligns with the manuscript's aim while using more cautious language than claiming direct confirmation of pulpal inflammation without a biological reference standard.

MATERIALS AND METHODS

This hospital-based diagnostic technology study was conducted in the dental unit of a tertiary care hospital in Bahawalnagar, Pakistan, to evaluate whether dynamic infrared thermal imaging could identify altered thermal behavior in permanent teeth affected by deep caries and whether these findings were associated with conventional pulp sensibility responses. The study was designed as a clinical observational diagnostic assessment in which each eligible participant contributed one deeply carious permanent tooth for evaluation. Where a sound contralateral tooth was available, it was assessed as an internal control to permit comparison of thermal recovery behavior within the same oral environment.

Patients presenting to the outpatient dental department with clinically and radiographically evident deep carious lesions in permanent teeth were screened consecutively during the study period. Eligible participants were those with at least one permanent tooth showing deep caries approaching the pulp without frank pulpal exposure, where the tooth was restorable, accessible for thermal imaging, and suitable for cold testing and electric pulp testing. Teeth were included when symptoms were absent or limited to mild, short-duration sensitivity, because the study focused on early or clinically doubtful pulpal involvement rather than advanced symptomatic disease. Teeth were excluded if they had obvious pulp exposure, swelling, sinus tract, severe mobility, advanced periodontal disease, periapical radiolucency, previous endodontic treatment, recent dental trauma, large restorations altering the crown surface, extensive coronal destruction, or any condition that could interfere with reliable thermal recording.

A consecutive sampling approach was used to reflect routine clinical presentation in a hospital dental setting. A total of 46 patients were included, and one deep carious permanent tooth was examined from each participant (12). Before enrollment, the study procedure was explained to each patient, and written informed consent was obtained. For younger participants, consent was obtained from a parent or guardian. Each participant underwent a standardized clinical assessment that included demographic recording, presenting complaint, tooth type, arch side, pain history, and symptom characterization. Patients were asked specifically about sensitivity to cold, heat, sweet foods, chewing discomfort, spontaneous pain, night pain, and persistence of pain after stimulus removal.

Clinical examination was performed using a mouth mirror, explorer, adequate illumination, and standard infection-control precautions. The carious lesion was assessed for depth, restorability, pulpal exposure, periodontal status, and signs of acute infection. Radiographic assessment was performed using periapical radiography or bitewing imaging where clinically indicated to confirm lesion depth, proximity to the pulp, and absence of periapical pathology. The study tooth was then selected for thermal imaging and pulp sensibility testing. When a contralateral sound tooth of comparable type was present, it was used as a control tooth for within-patient thermal comparison.

Thermal imaging was performed using a portable infrared thermal camera under standardized clinical conditions. Before image acquisition, participants were instructed not to consume hot or cold drinks for

at least 15 minutes. They were seated upright in the dental chair and allowed to rest briefly to permit stabilization of oral and tooth surface temperature. The operatory environment was kept stable during image capture, and direct airflow from fans, air-conditioning vents, or other sources was avoided. The tooth surface was gently cleaned and isolated with cotton rolls. Light drying was performed to remove excess moisture while avoiding prolonged dehydration of the enamel surface.

A baseline thermal image of the selected tooth was recorded before stimulation. The thermal camera was positioned at a fixed distance and angle as consistently as possible for all participants. A controlled cold stimulus was then applied to the tooth surface for a uniform short duration, after which serial thermal images were captured immediately and at defined intervals to observe the temperature drop and recovery pattern. Thermal assessment focused on dynamic recovery rather than a single static surface temperature. The primary thermal variable was recovery time, defined as the time required for the tooth surface temperature to return toward baseline after cold stimulation. Additional thermal variables included baseline temperature, post-stimulation temperature, temperature difference, and comparison with the corresponding control tooth where available.

After completion of thermal recording, conventional pulp sensibility testing was performed. Cold testing was carried out using a standard refrigerant applied to a cotton pellet and placed on the middle third of the crown. The patient's response was recorded according to both presence and duration of sensation. Responses were categorized as normal, exaggerated but non-lingering, lingering, or no response. Electric pulp testing was performed after isolation and drying of the tooth surface. A conducting medium was applied, and the stimulus was gradually increased until the patient first reported sensation. The first response reading was recorded as the electric pulp test value. Sensibility tests were interpreted in conjunction with clinical and radiographic findings rather than as standalone proof of pulpal status.

The main exposure condition was the presence of a deep carious lesion approaching the pulp in a permanent tooth without overt pulpal exposure. The principal outcome variables were thermal recovery time and temperature difference after controlled cold stimulation. Secondary variables included cold-test response category and electric pulp test reading. Age, sex, tooth type, and symptom status were recorded as descriptive clinical variables. Pulpal status was clinically categorized using the combined findings of history, clinical examination, radiographic assessment, cold response, electric pulp test response, and thermal behavior, with emphasis on identifying patterns consistent with early or doubtful pulpal involvement.

Bias was minimized through standardized patient preparation, uniform imaging sequence, controlled thermal stimulation, consistent tooth isolation, and performance of the thermal procedure by a trained operator using the same clinical workflow. Environmental influences were reduced by stabilizing room conditions, avoiding direct airflow, and limiting recent exposure to hot or cold beverages. Measurement variability was addressed by using a consistent camera position, defined imaging sequence, and structured recording sheet for all clinical and thermal variables. The use of contralateral control teeth where available helped reduce inter-individual variation in oral temperature and tooth surface characteristics.

Data were entered into a structured data sheet and checked for completeness before analysis. Quantitative variables, including baseline temperature, post-stimulation temperature, temperature difference, recovery time, and electric pulp test readings, were summarized using means and standard deviations where normally distributed. Categorical variables, including sex, age group, tooth type, symptom status, and cold-test response category, were summarized as frequencies and percentages. Thermal recovery time between deep carious teeth and control teeth was compared using paired or independent sample testing according to the structure of available control data. Differences in thermal parameters across cold-test response categories were assessed using appropriate group comparison tests.

Associations between recovery time and electric pulp test values were evaluated using correlation analysis. A p-value below 0.05 was considered statistically significant.

Ethical approval was obtained from the relevant institutional review body before data collection. Written informed consent was obtained from all participants or guardians where applicable. The study involved non-invasive thermal imaging and routine chairside pulp sensibility testing, and no invasive pulpal procedure was performed for research purposes. Patient confidentiality was maintained by anonymizing records and restricting access to study data. Data integrity was supported through standardized proforma-based collection, consistent examination sequence, careful entry of numeric values, and review of completed records before statistical analysis.

RESULTS

A total of 46 participants with one deeply carious permanent tooth each were included in the analysis. The largest age group was 26–35 years, comprising 18 participants (39.1%), followed by 18–25 years with 12 participants (26.1%), 36–45 years with 10 participants (21.7%), and participants older than 45 years with 6 cases (13.0%). The cumulative distribution showed that 30 of 46 participants (65.2%) were aged 35 years or younger, indicating that deep carious lesions in this cohort were most frequently represented among younger adults.

Table 1. Age Distribution of Study Participants

Age Group (Years)	Frequency (n)	Percentage (%)
18–25	12	26.1
26–35	18	39.1
36–45	10	21.7
>45	6	13.0
Total	46	100.0

Most affected teeth were posterior teeth. Molars accounted for 24 of 46 teeth (52.2%), making them the most frequently involved tooth type. Premolars represented 14 teeth (30.4%), while anterior teeth accounted for 8 teeth (17.4%). Overall, posterior teeth, including premolars and molars, represented 38 of 46 affected teeth (82.6%), showing a strong posterior predominance among deep carious lesions in the study population.

Table 2. Distribution of Affected Tooth Types

Tooth Type	Frequency (n)	Percentage (%)	Tooth Group
Anterior	8	17.4	Anterior
Premolar	14	30.4	Posterior
Molar	24	52.2	Posterior
Total	46	100.0	—

Thermal imaging demonstrated a longer mean recovery time in deep carious teeth than in control teeth. The mean thermal recovery time was 18.4 seconds in deep carious teeth compared with 11.2 seconds in control teeth, giving an absolute mean difference of 7.2 seconds. Expressed relatively, recovery time in deep carious teeth was approximately 64.3% longer than in control teeth. This indicates delayed return toward baseline temperature after thermal stimulation in teeth affected by deep caries.

Table 3. Comparison of Mean Thermal Recovery Time Between Deep Carious and Control Teeth

Group	Mean Recovery Time (Seconds)	Absolute Difference vs Control (Seconds)	Relative Difference vs Control (%)
Deep carious teeth	18.4	7.2	64.3
Control teeth	11.2	Reference	Reference

Temperature differences increased progressively across cold-test response categories. Teeth with a normal cold response had the lowest mean temperature difference at 0.6°C. Teeth with an exaggerated but non-lingering response showed a higher mean difference of 1.1°C, representing an increase of 0.5°C compared with normal-response teeth. Teeth with lingering response showed a mean temperature difference of 1.8°C, which was 1.2°C higher than the normal-response group. The highest mean temperature difference was observed in teeth with no cold response, at 2.2°C, corresponding to a 1.6°C

absolute increase and an approximately 266.7% relative increase compared with normal-response teeth. This pattern shows a graded thermal alteration across increasingly abnormal cold-test responses.

Table 4. Mean Temperature Difference According to Cold-Test Response

Cold-Test Response	Mean Temperature Difference (°C)	Absolute Increase vs Normal (°C)	Relative Increase vs Normal (%)
Normal	0.6	Reference	Reference
Exaggerated but non-lingering	1.1	0.5	83.3
Lingering	1.8	1.2	200.0
No response	2.2	1.6	266.7

The relationship between thermal findings and conventional pulp sensibility testing showed a consistent clinical direction. Longer thermal recovery time was associated with higher electric pulp test readings, indicating that teeth requiring longer time to return toward baseline temperature also tended to show altered sensibility responses.

Table 5. Summary of Key Thermal and Clinical Response Patterns

Parameter	Main Finding	Numeric Interpretation
Thermal recovery time	Higher in deep carious teeth than controls	18.4 sec vs 11.2 sec; difference 7.2 sec
Temperature difference by cold response	Increased across abnormal response categories	0.6°C, 1.1°C, 1.8°C, 2.2°C
Recovery time and EPT reading	Positive clinical pattern reported	–
Posterior tooth involvement	Predominant affected region	38/46 teeth; 82.6%

Overall, the results indicate that deep carious teeth showed altered thermal behavior compared with control teeth, most clearly demonstrated by a 7.2-second longer mean recovery time after stimulation. The thermal response also varied according to cold-test category, with mean temperature difference increasing from 0.6°C in normal-response teeth to 2.2°C in teeth with no response. These findings suggest that delayed recovery and greater post-stimulation temperature alteration were associated with progressively abnormal pulp sensibility responses in deeply carious permanent teeth.

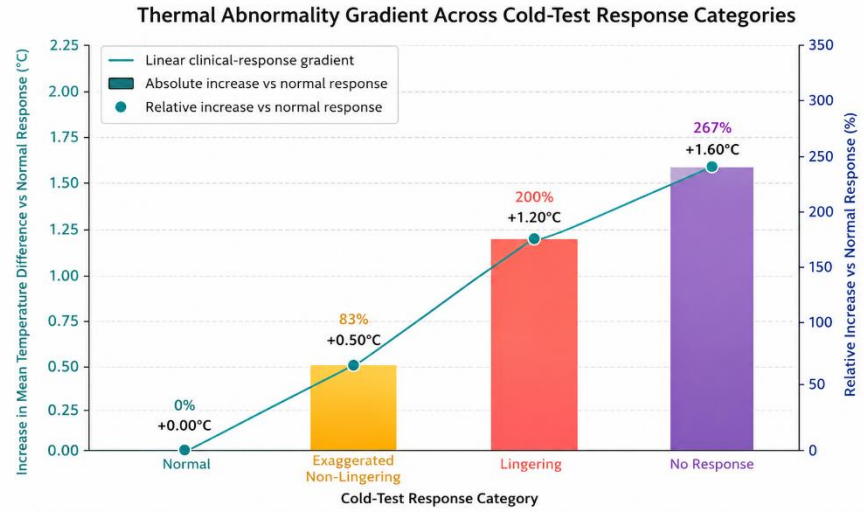

Figure 1. Thermal Abnormality Gradient Across Cold-Test Response Categories

The thermal abnormality gradient increased progressively across worsening cold-test response categories. Compared with teeth showing a normal cold response, the mean temperature difference increased by 0.5°C in teeth with an exaggerated but non-lingering response, 1.2°C in teeth with a lingering response, and 1.6°C in teeth with no response. In relative terms, this represented an 83.3%, 200.0%, and 266.7% increase above the normal-response reference level, respectively. This graded rise suggests a clinically meaningful escalation of thermal alteration as pulp sensibility responses became increasingly abnormal, supporting the role of dynamic thermal behavior as an adjunctive indicator of disturbed pulpal status in deep carious teeth.

DISCUSSION

Deep carious lesions create a diagnostic challenge because the clinical decision depends on whether the pulp remains capable of recovery or has progressed toward irreversible disease. In the present study, deep carious permanent teeth demonstrated altered thermal behavior compared with control teeth, most clearly shown by a longer mean thermal recovery time after stimulation. The mean recovery time was 18.4 seconds in deep carious teeth compared with 11.2 seconds in control teeth, indicating a 7.2-second delay and an approximately 64.3% longer recovery period. This finding suggests that teeth affected by deep caries may return toward baseline temperature more slowly than unaffected teeth, reflecting a disturbance in thermal regulation that may be associated with underlying pulpal vascular or inflammatory change. Because the pulp is a vascular connective tissue enclosed within rigid dentinal walls, early inflammatory changes may influence local heat exchange before advanced symptoms become clinically obvious. This supports the biological rationale for using dynamic thermal recovery, rather than a single static temperature reading, as an adjunctive marker of pulpal status (13,14).

The progressive increase in mean temperature difference across cold-test response categories further strengthens the clinical interpretation of the findings. Teeth with a normal cold response showed the lowest mean temperature difference at 0.6°C, while those with exaggerated but non-lingering response showed 1.1°C, lingering response showed 1.8°C, and no response showed 2.2°C. This stepwise pattern indicates that thermal alteration increased as conventional sensibility responses became more abnormal. Compared with the normal-response group, the temperature difference increased by 0.5°C in the exaggerated non-lingering group, 1.2°C in the lingering-response group, and 1.6°C in the no-response group. In relative terms, this corresponds to increases of 83.3%, 200.0%, and 266.7%, respectively. Such a gradient is clinically meaningful because pulpal disease is not a binary condition but a continuum ranging from normal pulp to reversible inflammation, irreversible inflammation, and necrosis. The observed thermal pattern therefore suggests that infrared imaging may capture physiological changes that parallel the worsening of pulp sensibility responses.

These findings are consistent with earlier thermographic research showing that tooth temperature behavior after stimulation may provide information about pulp vascularization. Paredes and colleagues reported that thermographic evaluation after thermal stimulation could help differentiate teeth according to vascular status, emphasizing recovery behavior as a more informative parameter than baseline temperature alone (15). Similarly, studies examining thermal imaging in vital and non-vital teeth, as well as odontogenic infection foci, have shown that altered tooth temperature patterns may be associated with underlying pathological conditions (16,17). The present findings extend this concept to deep carious teeth by showing that delayed recovery and increased temperature difference were evident in a clinical group where early or doubtful pulpal involvement is especially relevant. This distinction is important because the greatest value of a diagnostic adjunct lies not in obvious cases of advanced disease, but in clinically uncertain cases where symptoms are mild, absent, or inconsistent with lesion depth.

The relationship between thermal recovery and electric pulp test response also supports the clinical relevance of the thermal findings. Teeth with longer recovery times tended to show higher electric pulp test readings, suggesting that altered thermal behavior and altered neural sensibility may occur in the same direction. However, these two methods assess different biological dimensions. Electric pulp testing depends primarily on neural excitability, whereas thermal imaging may reflect surface temperature behavior influenced by vascular flow, tissue response, and heat transfer through enamel and dentin. This distinction is central to pulpal diagnosis because conventional sensibility tests do not directly measure pulp vitality. Systematic reviews have shown that cold testing and electric pulp testing have variable diagnostic performance, while vitality-oriented methods such as laser Doppler flowmetry and pulse oximetry may better reflect the true biological condition of the pulp (18,19). Thermal imaging may therefore occupy a useful intermediate position: it is non-invasive and clinically practical like

conventional tests, while potentially providing more physiological information than patient-reported sensation alone.

The predominance of posterior teeth in this cohort also has practical importance. Molars accounted for 52.2% of affected teeth, and premolars accounted for 30.4%, meaning that posterior teeth represented 82.6% of deep carious lesions. This distribution is clinically plausible because posterior teeth have pits, fissures, broader occlusal surfaces, and plaque-retentive anatomy that increase caries susceptibility. From a treatment-planning perspective, posterior deep caries is also where clinicians commonly face difficult decisions between selective caries removal, indirect pulp treatment, vital pulp therapy, and root canal treatment. Contemporary endodontic guidance emphasizes preservation of pulp vitality whenever possible and discourages unnecessary pulpectomy in teeth that can be managed conservatively (20,21). A rapid and non-contact adjunct such as thermal imaging may therefore be particularly valuable in posterior teeth, where lesion depth, patient symptoms, and conventional pulp test responses may not always provide a confident diagnosis.

The results should be interpreted as evidence of association rather than proof of histological inflammation. The study demonstrates that deep carious teeth showed delayed thermal recovery and greater temperature alteration, and that these thermal changes increased across abnormal cold-test categories. However, because pulpal inflammation was not confirmed histologically and no longitudinal outcome standard was used, thermal imaging cannot be described as a standalone diagnostic test for confirmed early pulpitis. A more accurate interpretation is that dynamic thermal imaging identified altered thermal patterns associated with suspected pulpal involvement in deep carious teeth. This distinction is important because overstatement of diagnostic certainty could lead to inappropriate clinical use. In practice, thermal imaging should be considered an adjunct to history, clinical examination, radiographic findings, cold testing, and electric pulp testing rather than a replacement for comprehensive pulpal diagnosis.

The clinical implication of these findings is that thermal imaging may help improve diagnostic confidence in cases where conventional findings are equivocal. A tooth with deep caries and no spontaneous pain may still show delayed thermal recovery or increased temperature difference, suggesting that the pulp is physiologically disturbed despite limited symptoms. Conversely, a tooth with a normal cold response and minimal thermal alteration may be more suitable for conservative pulp-preserving treatment. This approach aligns with minimally invasive dentistry, where the goal is to preserve pulpal health and tooth structure while avoiding both undertreatment and overtreatment. If future studies establish reproducible thresholds for recovery time and temperature difference, thermal imaging could support risk stratification in deep caries management and guide decisions regarding selective caries removal, liner placement, vital pulp therapy, or endodontic referral.

Several methodological factors may influence thermal imaging results and must be considered when interpreting the findings. Tooth surface moisture, enamel thickness, caries depth, restoration status, camera angle, imaging distance, room temperature, airflow, and duration of thermal stimulation can all affect recorded surface temperature. The use of patient preparation, isolation, controlled stimulation, avoidance of direct airflow, and comparison with contralateral control teeth helped reduce some of these sources of variability. Even so, the absence of reported standard deviations, confidence intervals, p-values, and category-specific sample sizes limits the ability to judge precision and statistical robustness. Similarly, the relationship between recovery time and electric pulp test values was clinically directional, but individual paired data would be required to calculate correlation coefficients, regression estimates, and diagnostic thresholds.

The study has strengths that support its relevance. It addresses a clinically important and common problem, uses a non-invasive technology, evaluates dynamic thermal recovery rather than relying only on baseline temperature, and compares thermal findings with routine pulp sensibility tests. The inclusion of patients with deep caries before advanced symptoms became dominant makes the findings

especially relevant to conservative treatment planning. At the same time, the small single-center sample, lack of a biological reference standard, absence of diagnostic accuracy measures, and limited inferential reporting restrict the strength of conclusions. Future research should include larger samples, standardized imaging protocols, examiner reliability assessment, longitudinal follow-up after treatment, and comparison with vitality-based methods such as pulse oximetry and laser Doppler flowmetry. Such work would help determine whether thermal recovery time can predict clinical outcomes and whether defined cut-off values can distinguish reversible pulpal change from irreversible disease.

Overall, the findings indicate that deep carious teeth showed a consistent pattern of delayed thermal recovery and increasing temperature difference across worsening pulp sensibility responses. These results support the concept that dynamic infrared thermal imaging may provide clinically useful adjunctive information in the assessment of suspected early pulpal involvement. Its greatest potential value lies in the early and uncertain stage of deep caries management, where preserving pulp vitality depends on accurate diagnosis and timely conservative intervention. The study therefore contributes preliminary evidence that thermal imaging may complement conventional pulp testing by adding a non-contact, painless, and physiologically oriented assessment of thermal behavior in deep carious permanent teeth.

CONCLUSION

Thermal imaging demonstrated promising adjunctive value for assessing early pulpal changes in permanent teeth with deep caries. Deep carious teeth showed delayed thermal recovery compared with control teeth, with mean recovery time increasing from 11.2 seconds in controls to 18.4 seconds in affected teeth. Thermal alteration also increased progressively across cold-test response categories, with mean temperature difference rising from 0.6°C in teeth with normal response to 1.1°C in exaggerated but non-lingering response, 1.8°C in lingering response, and 2.2°C in teeth with no response. These findings suggest that dynamic thermal recovery patterns are associated with increasingly abnormal pulp sensibility responses and may provide clinically useful information in cases where symptoms are absent, mild, or diagnostically uncertain. Thermal imaging should be interpreted as an adjunct rather than a standalone diagnostic test, but its non-invasive, painless, and repeatable nature may support earlier recognition of suspected pulpal involvement, improve diagnostic confidence, and assist conservative treatment planning aimed at preserving pulp vitality in deep carious teeth.

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