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The Diagnostic Value of Thermography in Oncology: Current Evidence and Future Perspectives

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ABSTRACT:
Introduction and Purpose: Thermography - imaging heat patterns via infrared (IR) cameras - offers a noninvasive, radiation-free approach to detect the increased regional skin temperature associated with tumors' hypermetabolism and angiogenesis [3]. This review examines the diagnostic potential of thermography in oncology, focusing on its role in early cancer detection and monitoring of treatment, and evaluates whether modern advancements address past concerns.
Material and methods of research: A thorough literature review was performed using PubMed and Web of Science.
Summary of Knowledge: Thermography detects infrared emission from the body's surface to map temperature distribution [3]. Breast cancer was the first field to embrace thermography [2]. Pilot studies in dermatology show IR thermography can differentiate melanoma from benign lesions [7]. In cancer monitoring, thermography appears promising: e.g. thermal imaging of breast tumors during therapy [8]. However, limitations include dependence on tumor depth, confounding factors [3], and lack of standardized protocols leading to variable results across studies [5, 6].
Conclusions: Thermography offers a physiologic imaging perspective that, with further validation and refinement, could enhance early cancer detection and real-time monitoring in oncology practice, rather than replace existing gold-standard methods.

Keywords: *termography, oncology, tumor, thermogram, inflammation*

INTRODUCTION

Early detection is crucial for improving cancer survival. For example, breast cancer - the most common malignancy in women (2.26 million cases worldwide in 2020) - has much higher survival rates when caught at early stages [3].

Standard screening tools like mammography and clinical exams significantly reduce mortality by identifying early, subclinical tumors. However, these anatomical imaging techniques have limitations: mammographic sensitivity drops in young or dense breasts, and it exposes patients to X-ray radiation [3]. Therefore, there is enduring interest in adjunctive, non-ionizing modalities that could detect cancers based on functional changes. Thermography, which produces infrared images of skin temperature, is one such modality that has been explored in oncology for decades. Its premise is that malignant tumors, through increased blood flow (angiogenesis) and metabolic activity, emit more heat than normal tissue [3]. This technique was first applied to breast cancer detection in 1956 by Lawson, who observed that the skin overlying breast tumors was 1.8–3.5 °C warmer than surrounding areas [2]. In the 1960s–70s, thermography was hailed as a cutting-edge tool and even gained U.S. FDA approval in 1982 as an adjunct to mammography [7]. Yet, subsequent studies yielded mixed results, and by the 1980s thermography's reputation suffered due to high false-positive rates and inconsistent sensitivity [5, 6]. Traditional thermographic cameras and protocols often lacked standardization, and in 2012 Health Canada and the U.S. FDA warned against using thermography as a standalone screening test [2].

Despite past skepticism, recent technological advances (high-resolution digital IR cameras with <0.05 °C thermal sensitivity [21], computer vision algorithms, and machine learning) have sparked renewed interest in medical thermography [3, 9]. Several contemporary studies suggest that thermography, when properly applied, might detect cancers in scenarios where traditional imaging is less effective (e.g. interval changes between mammograms, or in resource-limited settings without mammography access) [8, 9]. Moreover, thermography's ability to noninvasively monitor physiological changes has potential for tracking tumor response to therapy in real time [9]. These possibilities warrant a thorough re-examination of thermography's clinical value.

This review outlines the fundamental principles of thermography and its mechanism of action in detecting tumors, surveys the evidence for its applications in cancer diagnosis (breast and beyond), compares its advantages and limitations with other imaging techniques, and discusses future research directions and technological developments (including artificial intelligence integration and improved protocols). We aim to clarify which prior concerns about thermography remain valid and which might be overcome by new innovations, thereby defining the potential role of thermography in early cancer detection and monitoring moving forward.

DESCRIPTION OF STATE OF KNOWLEDGE

1. Fundamentals of Thermography and Mechanism of Action

Principles of IR Thermography: Medical thermography involves capturing infrared radiation emitted from the body's surface to create a temperature map (thermogram). Modern IR cameras convert heat emitted by skin into electronic signals, producing color-coded images of temperature distribution [3]. The spatial resolution and thermal sensitivity of current cameras are high – able to discern temperature differences as small as 0.025 °C [21] - enabling detection of subtle thermal asymmetries. Importantly, thermography is entirely noninvasive: it requires no contact, compression, or radiation exposure to the patient [3].

A standard thermographic examination involves the patient acclimating to room temperature for ~10–15 minutes disrobed, then obtaining images from various angles. Some protocols include "dynamic" thermography, introducing a temperature stimulus (e.g. a cold air challenge) and observing the rewarming pattern of skin, which can highlight abnormal vascular responses [3]. Digital processing can further enhance detection of thermal patterns and quantify temperature differences (ΔT) relative to baseline or contralateral regions.

Tumor Physiology and Heat Generation: The underlying mechanism linking cancer to elevated skin temperature is rooted in tumor physiology. Malignant cells proliferate rapidly and have high metabolic rates, resulting in increased production of heat. To sustain growth, tumors induce angiogenesis (new blood vessel formation) as described by Folkman's seminal work [3]. This leads to higher blood flow and vasodilation in tumor microcirculation. Cancer cells also release nitric oxide and other mediators that dilate vessels and disrupt normal vasomotor control [3]. The net effect is a region of hyperthermia overlying or adjacent to a tumor. In breast tissue, for instance, a growing tumor can cause overlying skin to become warmer by a few degrees. Early experimental studies confirmed this: Lawson's 1950s investigations showed breast tumors yielded skin temperature elevations around 2 °C compared to normal tissue [2]. Gautherie et al. later postulated that metabolic heat production correlates with tumor doubling time – faster-growing tumors emit more heat [20]. Thus, an infrared camera can indirectly "visualize" a tumor's functional activity by detecting these heat signatures. Importantly, this is a physiological imaging modality (detecting functional changes in perfusion and metabolism) rather than an anatomical one. It may flag abnormalities before a structural change is large enough to be seen on anatomical imaging [3], for example by detecting increased vascular activity in tissue that is mammographically unremarkable.

Normal and Pathological Thermal Patterns: In a healthy individual, skin temperature patterns are symmetrically distributed and reflect underlying vascular anatomy and heat loss. Any focal increase in skin temperature can signify pathology – not only cancer, but also inflammation, infection, or trauma. Thermography thus requires careful interpretation to distinguish malignant hyperthermia from other causes [3]. Commonly, a tumor might manifest on a thermogram as a localized hot spot or asymmetric warmer region. For breast thermography, a hallmark sign is unilateral hotter areas with angiomotor "spokes" – dilated blood vessels radiating from a tumor, sometimes described as a "vascular star" pattern. The dynamic response to cooling can also be evaluated: cancerous areas often rewarm more rapidly after a cold stimulus, due to disordered vasoregulation [5]. Advanced image analysis techniques can quantify features like temperature gradient, entropy, and vascular geometry from thermograms [8]. For instance, algorithms have been developed to calculate the entropy of tumor thermal patterns and track changes during therapy [8]. These quantitative metrics aim to improve objectivity in thermographic interpretation, addressing one historical criticism of thermography - that early use relied on subjective image reading.

In summary, thermography capitalizes on a basic biophysical property of tumors – heat generation – to provide a "heat map" of potential disease. It offers a window into the functional status of tissues: where there is abnormally increased perfusion and metabolism, there is a thermal signal that can be captured. The next sections explore how this principle has been applied in practice for cancer detection.

2. Application of Thermography in Cancer Diagnosis

Breast Cancer Screening and Diagnosis: Breast oncology is by far the most developed area of medical thermography. In the 1960s, breast thermograms were extensively studied as a screening tool. Initial results were promising, but subsequent controlled trials tempered enthusiasm. A pivotal 1977 study (the NCITN trial) found thermography's sensitivity lagged behind mammography for small cancers [21], contributing to its decline in clinical use. Nonetheless, interest persisted in using thermography as an adjunct rather than replacement. Modern digital infrared thermal imaging (DITI) has been re-examined in multiple breast centers worldwide. Some small-scale studies report excellent sensitivity: e.g. Arora et al. reported 97% sensitivity of a DITI system in 92 patients (with 58 cancers) [16]. However, in that study the specificity was only 44%, meaning many false positives. Parisky et al. conducted a large multicenter trial of dynamic IR imaging on 875 breast lesions recommended for biopsy [14]. Thermography correctly identified 181 of 187 cancers (97% sensitivity) but misclassified hundreds of benign lesions as suspicious, yielding only 14% specificity [14]. Such findings underscore that while thermography can be very sensitive in detecting breast abnormalities, its positive predictive value is low if used indiscriminately, leading to unnecessary biopsies. On the other hand, a normal thermogram has a high negative predictive value (~95% in Parisky's data) [14], suggesting thermography could potentially serve as a rapid rule-out test for significant breast disease when mammography is not available or is indeterminate.

Recently, there is focus on combining thermography with other information or techniques to improve accuracy. For instance, an Indian clinical study evaluated an AI-powered thermographic system (Thermalytix) as a pre-screening tool: among 147 women, this tool detected all 42 breast cancers, achieving 98% sensitivity, with 68% specificity [3]. Notably, it identified cancers even in women under 40 and those with no palpable lump [3]. This suggests thermography might pick up early vascular changes before tumors become palpable. In Armenia, Berberian et al. (2024) tested a portable smartphone-based thermal camera system for triage in 478 women [9]. When thermal results were combined with clinical breast exam findings, the system reached ~89% sensitivity and 83% specificity compared to mammography [9]. Such integrated approaches (thermal imaging + clinical factors or AI algorithms) appear far more promising than standalone thermography of the past. They could be particularly useful in low-resource regions where mammography access is limited [9]. It is important to emphasize that regulatory agencies only endorse thermography as an adjunct for breast screening. The FDA has stated thermography "has not been shown to be effective" as a standalone screening test [6] and must not replace mammograms. In practice, some specialized clinics offer adjunctive thermography for high-risk patients or for those who cannot undergo mammography. Additionally, thermography may have a niche in post-surgical or post-radiation breasts where scar tissue makes interpretation of mammograms challenging - a warmer area on a thermogram might warrant closer investigation.

Other Cancers – Dermatologic Applications:

Because thermography only detects surface temperature, its direct application is mostly limited to cancers near or involving the skin. Melanoma and other skin cancers can alter local skin perfusion and thus thermal patterns. A recent comprehensive review (Kesztyüs et al. 2025) noted that infrared thermography has been evaluated in dermatology for screening and diagnosing skin tumors [7]. Malignant pigmented lesions like melanoma often show higher temperature than benign moles. Magalhães et al. (2019) demonstrated that dynamic IR imaging (with cooling challenge) could distinguish melanomas from benign nevi with significant accuracy, improving diagnostic confidence [22]. Another study applied machine learning to 298 skin lesion thermograms and achieved improved classification of malignancies [7]. The overall evidence in skin oncology suggests thermography can be a supportive tool: for example, a suspicious mole that also shows a thermal abnormality might have a higher likelihood of being melanoma. However, thermography cannot visualize subsurface tumor extent or depth, so it complements rather than replaces dermoscopy or biopsy. A recent scoping review concluded that while infrared thermography is technically feasible for skin cancer screening, larger studies and 3D thermal imaging developments are needed before routine use [12]. Still, case reports have shown thermography detecting subclinical inflammation around basal cell carcinomas and aiding in defining margins for surgery [7]. Given its non-contact nature, dermatologists are researching thermography as an adjunct in teledermatology – a high-resolution thermal camera could potentially flag concerning lesions remotely.

Head and Neck Tumors: An emerging application is in oral and maxillofacial oncology. Cancers inside the oral cavity or in the maxillofacial region can produce asymmetric facial heat patterns. Preliminary work by Chakraborty et al. (2016) used facial thermography and texture analysis to detect oral cancer, achieving ~86% classification accuracy in distinguishing cancer patients from normals [11]. More recently, Mačianskytė et al. (2022) developed an automated algorithm to analyze thermal images of patients with oral tumors; it showed 78% sensitivity and 95% specificity in identifying tumor presence, nearly matching the accuracy of CT scans [24]. These findings, albeit in small cohorts, illustrate thermography's potential as a non-invasive screening for oral cancers – which is especially valuable in settings where many patients delay invasive tests like biopsy. Infrared imaging could, for example, be used by dentists or primary care providers to triage which patients with oral lesions need urgent specialist referral. In thyroid nodules or head-neck lymph nodes, thermography has been less studied; deeply situated nodes may not affect surface heat unless large or inflammatory. However, some researchers have examined IR thermography to detect hypermetabolic thyroid nodules, with mixed results due to neck musculature and variable skin thickness. Generally, any tumor that is superficial or causes vascular changes in the skin could be a candidate for thermographic detection.

Whole-Body or Other Applications: There have been exploratory attempts to use thermography for other malignancies – for instance, mapping abdominal skin for underlying liver tumors, or using thermography in breast cancer risk assessment. A famous long-term study by Gautherie in the 1980s found that women with abnormal breast thermograms but no clinical cancer had a significantly higher 5-year risk of developing breast cancer.

This suggests thermography might identify a pro-cancerous state (e.g. increased vascularity possibly from atypical cells) even before a tumor is detectable [20]. While intriguing, this risk-prediction use is not part of standard guidelines, due to lack of controlled trial evidence. Whole-body thermography (scanning the patient head-to-toe) is offered by some alternative clinics as a general cancer screening, but this is not supported by data – internal organ cancers (lung, colon, etc.) rarely produce a discernible skin heat signature until very advanced (e.g. a fungating skin-invading tumor). Therefore, current legitimate uses of thermographic diagnosis in oncology are concentrated in breast and skin cancers, and to a lesser extent oral/head-neck cancers. These are domains where either screening or early diagnosis could benefit from an adjunct functional imaging modality. In sum, thermography's diagnostic applications are feasible but need to be targeted appropriately to tumor types and patient populations where its strengths (safety, sensitivity to perfusion) outweigh its weaknesses.

3. Advantages and Limitations Compared to Other Techniques

Advantages of Thermography: Thermography offers several appealing advantages relative to conventional imaging techniques:

- Non-Invasive and Safe: Thermography involves no radiation, no contrast injections, and no physical contact. This makes it repeatable with no cumulative risk – patients can undergo serial thermographic exams as often as needed without harm [3]. In contrast, mammography (X-ray) carries a small radiation dose and cannot be done too frequently, and MRI requires gadolinium contrast and long scan times. Thermography's safety is especially beneficial for young women, for whom repeated radiation exposure is undesirable, and for pregnant or breastfeeding patients who cannot undergo routine X-rays [3].
- Patient Comfort and Accessibility: A thermographic scan is quick (imaging can be done in minutes) and painless. There is no breast compression (which causes discomfort in mammography) and no confining machine (as in MRI). This can improve patient compliance with screening, particularly for those who avoid mammograms due to pain or anxiety. The equipment is relatively portable; modern IR cameras are compact and even smartphone attachments exist [8]. This portability means thermography could be deployed in community clinics or remote areas, expanding access to screening. The cost per examination is low after the initial camera purchase, making it economically attractive for population screening or frequent monitoring. One review noted thermography devices are far less expensive than mammography units and require minimal maintenance [3].
- No effect of Breast Density: A major limitation of mammography is reduced sensitivity in radiologically dense breasts (common in younger women) [3]. Dense tissue appears white on X-ray, like tumors, masking small lesions. Thermography, however, is unaffected by breast density because it does not rely on tissue X-ray contrast – it detects functional changes. Fibrocystic changes or implants that impede mammographic interpretation do not hinder thermograms [3]. Thus, thermography can theoretically screen women of all ages and breast types, filling a gap where ultrasound or MRI is often used as supplemental screening in dense breasts.

- Early Functional Changes: Thermography can potentially signal an abnormality earlier than structural imaging. It can detect angiogenesis and hypermetabolism - processes that occur in the transition from normal tissue to malignancy. Some proponents argue that a growing tumor triggers measurable thermal changes before it becomes a detectable mass on imaging. Indeed, cases have been reported where thermography indicated a hotspot and cancer was diagnosed 1–2 years later at that site. While anecdotal, this suggests thermography could serve as an "early warning" for heightened surveillance. Similarly, in monitoring, a sudden thermal change might indicate recurrence or progression before sizes change on CT/MRI.
- Real-Time and Large Area Scanning: Thermography produces results in real-time – images are available immediately during the exam. This can allow on-the-spot decisions (for example, doing further tests if a thermal abnormality is seen). Moreover, thermography can cover large fields of view at once. For instance, a single thermographic image might capture an entire torso or limb, screening for any hotspots in one shot, unlike targeted ultrasound which examines one area at a time. This broad view can be useful for detecting multi-focal disease or assessing bilateral symmetry.

Despite these advantages, thermography has significant limitations that have prevented its adoption as a primary diagnostic tool:

- Limited Specificity and False Positives: Thermography's biggest pitfall is that heat is a non-specific indicator. Many benign or physiological conditions can cause thermal anomalies. For example, infections like mastitis or abscesses, benign tumors with high vascularity (like fibroadenomas), or even recent physical activity can raise skin temperature [3]. In breast imaging, thermography might flag hormonal fluctuations or inflammation as "hot spots" leading to false alarms. The difficulty in distinguishing cancerous heat from other heat means standalone thermograms have a high false-positive rate in screening populations. This was seen in trials like Parisky's (specificity 14% in a high-risk group) [14]. High false positives not only cause anxiety and additional tests but also undermine the test's credibility. Thus, thermography's positive findings must be correlated with anatomic imaging or clinical exam for specificity - a workflow that complicates its use.
- False Negatives and Depth Limitations: Tumors that do not induce much surface temperature change can be missed. Small, deep-seated cancers (e.g. a small tumor deep in a large breast, or an intra-thoracic tumor) might not produce a discernible thermal signature on the skin. Cancers that grow mainly by local invasion rather than angiogenesis (like some lobular breast carcinomas) might be thermographically "cold". Notably, thermography is blind to microcalcifications, an early sign of breast cancer detectable by mammography. Indeed, the few false negatives in IR studies were often pure microcalcification lesions with no mass or blood flow [14]. Therefore, thermography cannot be relied on to definitively rule out cancer, especially those without prominent angiogenesis. Lack of a thermal abnormality does not guarantee absence of malignancy - it must be interpreted in context (this is why it's adjunctive).

- Environmental and Technical Factors: Proper thermographic imaging requires controlled conditions. Room temperature, airflow, and even wall color (for reflected IR) can affect results. Patients' skin must be bare and dry (no lotions, which can alter emissivity). If a patient is flushed from coming in from heat or exertion, or if they recently smoked or drank hot beverages, skin temperatures can be globally altered. All these variables demand standardized protocols – any deviation can lead to inconsistent images. Early thermography suffered from poor standardization, leading to variable accuracy across different clinics [17]. Furthermore, the interpretation historically required specialized training, and results could be subjective. While AI is helping to mitigate this, not all centers have validated software, and regulatory standards for thermographic devices are not as rigorous as for mammography [28]. In fact, as of now, thermography clinics are not held to uniform quality control in many countries (mammography centers, by contrast, must meet strict FDA/MQSA standards in the U.S.) [28].
- No Proven Impact on Outcomes: A fundamental limitation is the lack of evidence that thermographic screening improves long-term outcomes (e.g. survival). Unlike mammography, which has randomized trial data showing mortality reduction, thermography has never been shown to save lives in a controlled study [28]. This makes clinicians hesitant to recommend it as part of standard care. Without outcome data, insurance and guidelines do not endorse thermography, and it remains on the fringes of mainstream medicine. For example, a 2012 systematic review concluded there was "insufficient evidence" that thermography added any benefit to mammography or clinical exam [15]. Large trials would be needed to change this, but conducting a thermography vs. mammography trial may be unethical given mammography's known benefits.
- Adjunctive Use Still Requires Gold-Standard Follow-up: A practical limitation is that any abnormal thermographic finding necessitates confirmation with established diagnostic methods (imaging or biopsy). As MD Anderson's experts noted, "there's no way to follow up abnormalities with thermography" alone [28]. A patient with an abnormal thermogram must "start over" and get a mammogram or ultrasound [28]. This reduces the standalone utility of the test – it cannot pinpoint lesion location or type, so additional tests are unavoidable. In essence, a positive thermogram is an indication to do the very tests one might have been trying to avoid. For this reason, some argue thermography adds cost or delays rather than streamlining care, if used inappropriately.

In summary, thermography's non-invasive nature and potential sensitivity are counterbalanced by issues of specificity and evidence. It excels in safety and can pick up functional changes, but it cannot match the anatomic detail and proven efficacy of modalities like mammography, ultrasound, or MRI. Table 1 below contrasts key features:

Table 1. Comparison of Thermography and Other Breast Imaging Modalities

Feature	**Thermography (IR)**	**Mammography (X-ray)**	**Ultrasound**	**MRI**
Radiation/ Contact	None (safe, no contact)	Low-dose X-ray (breast compression required)	None (sound waves, contact via probe)	No ionizing radiation (magnetic fields, IV contrast often)
Sensitivity (early lesions)	Can detect physiological changes (angiogenesis), but may miss non-vascular lesions [3]	High for calcifications & masses >2-3mm, reduced in dense tissue [3]	Good for masses (esp. in dense breasts), poor for calcifications	Very high (detects most lesions > few mm, including DCIS), often oversensitive (benign enhancements)
Specificity	Low if used alone (many false positives from benign heat) [3]	Moderate (overlaps in appearance of benign vs malignant on X-ray)	Moderate (benign cysts vs solid can mimic)	Moderate (enhancement patterns not 100% specific)
Patient Comfort	Excellent (painless, quick)	Moderate (compression discomfort)	Good (mild pressure from probe)	Poor (long exam in bore, possible claustrophobia, IV injection)
Effect of Breast Density	None [3]	Decreased sensitivity in dense tissue [3]	Not affected (sound transmission might even be better in dense tissue)	None (density not an issue)
Cost & Accessibility	Low-cost device, can be portable[3]; minimal operating cost	Expensive machine, requires radiologist; widely available in developed countries	Moderate cost; widely available; operator-dependent	Very high cost; limited to specialized centers
Regulatory Approval	As adjunct only (FDA-cleared adjunct device) [6]	Gold-standard (FDA-approved for screening)	Standard adjunct diagnostic tool	Adjunct (e.g. high-risk screening)

Proven mortality benefit	Not demonstrated (no RCTs) [28]	Yes (RCTs show mortality reduction)	No (no screening trials, used for targeted diagnostics)	Not in general population (benefit in high-risk BRCA carriers shown)

Key: DCIS = ductal carcinoma in situ (non-invasive early cancer).

In essence, thermography's ideal role is complementary – leveraging its strengths (safety, ability to detect functional change) in conjunction with structural imaging to improve overall diagnostic accuracy, rather than using it in isolation.

4. Future Research Directions and Technological Developments

Thermography in oncology is at a crossroads where technology and clinical insight must converge to realize its potential. Several promising directions are being pursued:

Integration of Artificial Intelligence (AI): The advent of AI and deep learning has arguably been the biggest game-changer for thermography. Machine learning algorithms can analyze complex thermal patterns and discern subtle differences beyond human visual perception [9]. Researchers have developed AI models to automatically detect breast cancer from thermograms with very high accuracy on experimental datasets [3]. For example, Mohamed et al. (2022) trained a deep convolutional neural network on a large thermal breast image database (DMR-IR) and reported 100% sensitivity and 98.7% specificity in distinguishing cancer vs normal in that dataset [10]. While such near-perfect performance in a controlled setting may not directly translate to real clinics, it demonstrates the capability of AI to greatly improve interpretation. AI can also reduce operator dependency – making thermography more standardized. Current and future AI tools are being designed to identify not just the presence of a thermal anomaly, but also characteristics like shape, symmetry, and rate of temperature change. This could allow thermography to yield quantitative risk scores, similar to how mammography has BI-RADS categories. Thermal images analyzed by AI might flag patterns consistent with malignancy that a human might overlook. Additionally, AI can combine thermographic data with other patient information (age, genetic risk, symptoms) for more robust predictive modeling [9]. The success of systems like Thermalytix in clinical tests is a harbinger of AI-driven thermography becoming a viable screening adjunct, especially in telemedicine or point-of-care scenarios.

Smartphone and Portable Thermography: As noted, infrared sensors are becoming compact and inexpensive. Researchers envision a scenario where women could use a simple thermal camera attachment on a smartphone at home to perform monthly breast thermography, with an app guided by AI analyzing the images [8]. Gannot et al. (2018) have indeed piloted a smartphone-based system for breast cancer early warning, aiming to fill the gap between annual mammograms [8]. By detecting any new hot spots early, such a system could prompt timely medical evaluation. For global health, portable thermography devices can bring cancer screening to underserved areas. A study in Armenia using a smartphone thermal camera showed feasibility for triaging patients, as discussed earlier [9].

3D Thermography and Tomographic Reconstruction: A limitation of current thermography is that it provides a 2D projection of surface temperatures. Emerging research is exploring thermal tomography, where multiple cameras or moving cameras capture images from different angles to reconstruct a 3D temperature map of a body part [7]. This could help localize a heat source in three dimensions (depth estimation) rather than just the surface location. For instance, a breast could be imaged from multiple sides and computational models used to infer the location and size of a sub-surface tumor causing the observed surface heating. Wu et al. (2017) used a prototype "thermal tomography" system to monitor breast tumors during neoadjuvant chemotherapy, obtaining quantitative parameters (like ΔT differences and novel indices) that correlated with pathological response [18]. As computation power grows, we may see thermography combined with biophysical modeling of heat conduction in tissues to pinpoint deeper tumor sites. Similarly, high-frame-rate thermal videos (thermal imaging in motion) could analyze vascular pulsation or dynamics of blood flow, adding another layer of functional data to static temperature readings.

Multimodal Imaging and Fusion: The future likely lies in combining thermography with other modalities to augment overall diagnostic performance. One approach under investigation is fusing thermal images with optical images (digital photographs) or ultrasound images to get both functional and anatomical information. For example, a suspicious area might be evaluated with a hybrid device that does ultrasound and thermography simultaneously, overlaying temperature maps on the ultrasound image. Another area is combining thermography with fluorescence imaging or photoacoustic imaging to cross-verify areas of high metabolic activity. There is also interest in integrating thermal data into radiology AI models that already use mammograms or MRI – essentially giving an AI both an anatomical and a thermal channel to improve cancer detection.

Thermography for Treatment Monitoring and Personalized Therapy: Beyond detection, a significant future application is in monitoring cancer treatments. We already discussed how Israeli researchers demonstrated thermography to monitor radiotherapy response in breast tumors [8]. In that study, thermal entropy and vascular "arms" visibly reduced in responders during the course of radiationn [8]. Building on this, larger trials are being planned to validate thermographic monitoring for radiotherapy, chemotherapy, and even immunotherapy [8]. A vision for the future is using thermography in the oncology clinic to get immediate feedback: for instance, after a chemo infusion, a quick thermal scan of the tumor site might show reduced heat if the drug is effective (due to lowered metabolism), or increased inflammation if a robust immune response is occurring. This noninvasive feedback could allow rapid tailoring of treatment – switching ineffective therapies sooner or confirming effective ones. It might also detect complications like tumor site infection or phlebitis earlier via heat changes. Thermography could also aid in surgery – for example, during breast-conserving surgery, a thermal camera might help ensure all hypermetabolic (hot) tissue is removed, serving as an "oncologic margin" check in real time. Some pilot studies with liquid crystal thermography in surgery have attempted to delineate breast tumor margins by temperature differences [25]. Although in early stages, these techniques highlight how thermography might find a place in intraoperative decision-making.

Standardization and Clinical Trials: For thermography to become mainstream, standardization is crucial. Future efforts are focusing on establishing uniform protocols (room temperature, patient prep, camera calibration) and certified training for thermographic imaging. The development of consensus guidelines (potentially by professional bodies in radiology or surgical oncology) will help ensure that results are reproducible across centers. Additionally, well-designed clinical trials are needed. For example, a prospective trial could evaluate adjunctive thermography in a high-risk screening program: do MRI + thermography together detect more early cancers than MRI alone? Or a trial could test thermography as an interval surveillance tool between mammograms in large populations, measuring if interval cancers (cancers arising between regular screenings) are caught earlier. Outcome measures like tumor size at detection or stage shift could be assessed. Such evidence will be key to convincing guideline committees to incorporate thermography. Some ongoing studies include the use of thermography plus AI in community breast screening in India, and trials of thermography for skin cancer screening in Europe [7]. The results in the next 5–10 years will clarify its real-world performance.

Technological Innovations: On the hardware side, we anticipate continuous improvement in IR detector technology - higher resolution sensors, faster frame rates, and better noise reduction, all at lower cost. Emerging IR materials and sensors (such as microbolometers) might allow even finer temperature discrimination. Some researchers are exploring mid-IR and long-IR spectral imaging to get different depth information. Others are looking at dual-modality cameras that capture both infrared and visible or ultraviolet images for more context. Moreover, cloud computing and connectivity mean large thermographic datasets can be aggregated for machine learning, accelerating algorithm improvement. The end goal is a robust, affordable system that can be widely deployed with confidence.

In summary, the future of thermography in oncology likely hinges on synergy – synergy with AI, with other imaging, and with clinical workflows. The concept of a "thermographic biopsy" (a noninvasive thermal characterization of tissue) is becoming more plausible as technology and understanding advance. If current research succeeds, thermography could evolve from an alternative screening test of the past into a valuable component of multi-faceted cancer care in the future, aiding in early detection, risk stratification, and real-time monitoring in a personalized manner.

DISCUSSION

Thermography in oncology has traversed a tumultuous path – from early enthusiasm decades ago to skepticism and now a cautious resurgence. This review underscores that infrared thermography does possess unique diagnostic potential: it is safe, patient-friendly, and capable of highlighting the physiological aberrations that often accompany malignancy. In particular, for breast cancer (where it has been most studied), thermography can detect the increased heat of tumor-induced blood flow and may serve as a helpful adjunct for early detection in certain scenarios, such as in dense breasts or for individuals who cannot undergo routine mammograms. Additionally, emerging applications in skin cancer and oral cancer detection broaden the scope of thermography beyond its historical niche.

Thermography's ability to monitor dynamic changes offers an appealing tool for tracking treatment responses - potentially providing oncologists with rapid feedback on whether a tumor is responding to therapy or not, well before anatomical imaging changes become evident [8].

However, it is equally clear that thermography alone is not a panacea. Its limitations - chiefly the risk of false positives and negatives - mean that it cannot replace established imaging modalities at present [6, 28]. The consensus of current evidence and expert guidelines is that thermography should only be used in conjunction with, not instead of, methods like mammography, ultrasound, or MRI. The skepticism from regulatory agencies arises from the lack of proof that thermography improves outcomes when used as a standalone screening test [28]. As such, any clinical use of thermography today should be as part of a complementary strategy. For instance, a breast clinic might use thermography as an initial triage tool or to supplement assessments, but a diagnosis must ultimately be confirmed with biopsy or standard imaging.

FUTURE PERSPECTIVES

Looking ahead, ongoing improvements are steadily addressing the traditional pitfalls of thermography. Modern high-resolution cameras, rigorous imaging protocols, and AI analysis are elevating both the sensitivity and specificity of thermal imaging to levels that were not previously attainable. Preliminary clinical research, as reviewed, shows that these advances can substantially reduce human error and improve diagnostic accuracy [9, 10]. The integration of thermography into multi-modal diagnostic algorithms is a promising approach to leverage its strengths while mitigating weaknesses. Large-scale studies are anticipated in the near future, and their outcomes will be pivotal. Should these studies demonstrate that adjunctive thermography leads to earlier cancer detection or more effective monitoring (and thereby better patient outcomes), we can expect a shift in clinical practice paradigms.

CONCLUSION

Thermography represents a fascinating intersection of technology and tumor biology. It offers a window into the functional state of tissues that, when interpreted with modern tools, can enrich our diagnostic and monitoring capabilities. While it is not poised to supplant conventional imaging, it has carved out a potential role as a supportive modality in the early detection and follow-up of cancer. Clinicians and researchers must maintain a balanced view - embracing innovation and data-driven integration of thermography, but also adhering to evidence-based medicine to ensure patients receive the best proven care. With ongoing research and technological refinement, infrared thermography may yet fulfill its promise as a valuable ally in the fight against cancer, enabling us to see cancer's heat and use it to our patients' advantage.

AUTHOR'S CONTRIBUTIONS

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CONFLICT OF INTEREST

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