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Infrared thermography in clinical practice: a literature review

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Abstract

Background Infrared thermography technology is a diagnostic imaging modality that converts temperature information on the surface of the human body into visualised thermograms. This technology has the capacity to intuitively detect the presence of certain abnormal conditions or foci in the human body. In recent years, the application of this technology in medicine has become increasingly extensive, especially in the areas of auxiliary diagnosis and early screening of diseases.

Objectives The aim of this review is to analyse and summarise the application of infrared thermography in clinical practice.

Methods A comprehensive search of the research literature pertaining to the clinical application of medical infrared thermography was conducted, encompassing publications by both domestic and foreign researchers and scholars, in prominent databases including PubMed, ISI Web of Science, and CNKI since the inception of these databases.

Results A total of 51 articles were ultimately included in the study. The application of infrared thermography has been demonstrated in oncology, painful diseases, inflammation, rheumatism, and vascular-related diseases.

Conclusions The extensive utilisation of infrared thermography in clinical settings signifies the technology's considerable potential. Addressing its current limitations can optimise its benefits.

Keywords Infrared thermography, Clinical applications, Limitations, Development prospects

Theoretical basis

The field of medical infrared thermography has been the subject of research for several decades. Previous studies have demonstrated that infrared radiation occupies the frequency range between visible light and microwave radiation in the electromagnetic spectrum. The human body typically emits infrared radiation within the wavelength range of 8–14 μm, which can be detected using infrared detectors [1]. This emitted thermal radiation is then converted into a visible, quantifiable infrared thermal image. It is a well-established scientific fact that any object with a temperature above absolute zero (− 273.15 °C) emits infrared radiation [2], and as a homeothermic organism, the human body inevitably produces such radiation. The core function of medical infrared

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thermography [3] is to convert this invisible infrared radiation into a tangible, visible thermal image.

Currently, medical infrared thermography (IRT) is a comprehensive and advanced technology [4]; it is highly sensitive to temperature changes, with instruments capable of detecting even the smallest variations, which are then represented as thermal images. These images display temperature gradients, with colors corresponding to temperatures from high to low, typically ranging from dark red, red, light red, yellow, green, light blue, dark blue, to black.

The human body releases energy through its metabolic processes, with the majority of this energy being released outside the body in the form of heat. The skin, which is the largest organ of the body, is capable of dissipating heat through various mechanisms such as radiation, conduction and convection, and evaporation. Among these mechanisms, radiation is the most effective in dissipating heat. Consequently, an infrared thermogram, which is obtained by converting infrared radiation, can serve as a measure of the human body's metabolic rate. The body's thermoregulatory mechanism involves the control of vasoconstriction through the sympathetic nervous system to regulate blood flow [5]; thus, human skin temperature is determined by blood flow and blood temperature. Consequently, factors that affect the vasodilation and contraction of the skin (e.g., diseases, injuries, etc.) [6] will inevitably affect the body's infrared radiation as well.

Imaging tests typically detect lesions that have progressed to a certain stage, where organic damage to tissues and organs is already evident. In contrast, IRT technology can identify changes in the affected area prior to the appearance of organic lesions. Human infrared radiation is governed by specific physiological mechanisms and structural factors, intimately linked to intrinsic processes such as energy metabolism, body heat balance, thermoregulation, and circadian rhythms. These factors, along with emotions and physiological activities, can influence thermal imaging results. Extrinsic factors, such as external temperature, airflow, and humidity, also play a role. Under normal conditions, temperature symmetry is observed between the left and right sides of the body, with the torso, head, and neck typically exhibiting higher temperatures compared to the limbs. Regions with higher fat accumulation tend to show lower surface temperatures, which may reduce the accuracy of thermal imaging in individuals with significant obesity. In addition, the surface temperature of females is generally slightly higher than that of males. When analyzing thermograms, these factors must be taken into account, and the analysis should be integrated with the patient's clinical symptoms for precise lesion localization. It is most accurate to compare current thermograms with the patient's baseline thermogram, taken prior to illness, to identify temperature differences while accounting for intrinsic and extrinsic influences. For instance, temperature asymmetry between the breasts may signal pathological changes [7], and a slight temperature decrease [8] in a localized area may serve as an early indicator of pressure damage.

Medical thermography is capable of detecting even the smallest temperature differences between symmetrical body regions or between diseased and healthy states. With the continuous advancement of science and technology, the sensitivity and convenience of IRT imaging have significantly improved, resulting in more diversified information reflected in the acquired thermograms. As a result, its application scope has expanded across various medical fields. IRT provides a comprehensive analysis of the thermal metabolic changes in human cells, tissues, organs, and systems, offering valuable insights into the overall health status of the body. This emerging technology can serve as a complementary tool alongside traditional imaging diagnostic methods, such as X-ray, B-ultrasound, and CT, offering cross-validation and corroboration of results. Compared to these conventional imaging techniques, IRT offers clear advantages in terms of portability, non-invasiveness, simplicity, absence of cost-effectiveness [9], and ionizing radiation.

Clinical applications

IRT in oncology

Tumors are a category of diseases characterized by the abnormal proliferation of cells, with the most notable feature being the formation of a localized mass. This mass arises when tissue cells proliferate to form neoplastic growths that exhibit a significantly faster metabolic rate compared to the surrounding normal cells. Such abnormal metabolic activity enables tumor detection through traditional imaging techniques, such as bone scanning and PET-CT. The anastomosis of neoplastic tissue and arteriovenous networks generates localized heat [10], detectable through IRT, which aids in differential diagnosis.

Breast cancer

Initially applied in the diagnosis of breast cancer, IRT has proven effective in identifying malignant tumors, offering an alternative to conventional diagnostic methods like X-ray, CT, and MRI, although different modalities may yield contradictory results [11].

In a study conducted over a decade ago, Liu [12] conducted IRT on 11,200 patients with breast diseases and healthy individuals, with pathological confirmation. Of the 150 pathologically confirmed breast cancer cases, 134 were identified as positive by IRT, yielding a diagnostic

compliance rate of 89.3%.Zhou [13] demonstrated that the specific mathematical mean values derived from infrared thermograms of the breast region correlated directly with the severity of different breast diseases. The mean values followed this order: normal breast < solid cysts and hyperplasia < fibroids < breast cancer. As the mean values increased, the distribution of red areas in the infrared thermograms became more pronounced. These findings underscore the high clinical value of IRT in breast cancer screening, early detection, and differential diagnosis.

Skin cancer

Magalhães [14] observed that IRT has been effectively employed in distinguishing benign and malignant tumors, as well as various types of skin cancers, based on a review of relevant thermography studies. Kesztyüs's [15] study of the literature on the use of IRT for skin cancer screening in recent years has also revealed that IRT provides additional information about thermal radiation on the skin surface in comparison to digital photography. This additional information is strongly correlated with the extent of malignant lesions on the skin surface. Godoy et al. [16] introduced a dynamic thermography (DTI) technique for skin cancer detection, which improves sensitivity and specificity. The method identifies pixels with the same initial temperature, overcoming cooling device limitations. A study with 102 adults showed 95% sensitivity and 83% specificity in identifying skin diseases, with an AUC of 95%. DTI, with precise pixel selection, could be a rapid, accurate, non-contact, non-invasive screening method, potentially reducing the need for biopsies in suspicious lesions.

Oral cancer

A research team led by Bhowmik [17] has developed a low-cost, portable device that uses infrared thermography to visualise blood flow to facilitate the detection of subepidermal cancers in resource-limited areas. The device was tested in a double-blind study, where it effectively discriminated between oral cancer patients and those with pre-cancerous conditions. The results showed that the test achieved an overall sensitivity of 96.66% and a specificity of 100% compared to the gold standard of biopsy. The study also concluded that the test not only complements existing imaging modalities, but also offers significant predictive accuracy.

Head and neck cancer metastases

In a pre-planned clinical trial [18], 90 patients with oral cancer and suspected cervical lymph node metastases underwent infrared imaging prior to undergoing neck dissection surgery. A non-inferiority analysis was performed between an automated analysis of an entropy gradient support vector machine (EGSVM)-driven infrared thermography system and conventional CT scanning. The EGSVM-based automated analysis demonstrated superior performance with higher sensitivity (84.8% vs. 71.7%), specificity (77.3% vs. 72.7%), and overall accuracy (81.1% vs. 72.7%) when compared to manual qualitative assessment. Furthermore, EGSVM enhanced the positive predictive value (79.6% vs. 73.3%) and negative predictive value (82.9% vs. 71.1%) in comparison to manual analysis. The findings of the study demonstrated that EGSVM-based automated analysis exhibited higher sensitivity and specificity in comparison with enhanced CT. Consequently, the EGSVM-based infrared thermography system has the potential to serve as a non-invasive, radiation-free alternative modality for the detection of lymph node metastasis in patients with oral cancer.

Limited choroidal hemangiomas

In addition, IRT demonstrates significant potential in diagnosing microscopic tumors. For instance, in the detection of limited choroidal hemangiomas, Balasubramaniam [19] found that 95.5% of patients with this condition exhibited vascular rings in their thermograms, highlighting the high sensitivity of infrared thermography in diagnosing this disease.

Thyroid cancer

Dingshan [20] simultaneously applied color Doppler ultrasound and IRT to examine 88 patients with thyroid disorders. The findings revealed a diagnostic compliance rate of 79.5% for color ultrasound, 71.6% for IRT, and 90.9% for the combined approach. While clinicians primarily rely on color ultrasound and clinical experience for diagnosing thyroid diseases, which are inherently more subjective, incorporating infrared thermal imaging significantly enhances diagnostic sensitivity, thereby improving diagnostic accuracy.

Specific studies related to the use of IRT in oncology are listed in Table 1.

IRT in inflammation

Inflammation is a protective response of the body, characterized by redness, swelling, heat, pain, and dysfunction. It can be classified into infectious and non-infectious types. Typically, inflammation serves as a beneficial defense mechanism, yet it can also be harmful, such as when the body attacks its own tissues or when it occurs in transparent tissues. During inflammation, vasodilation leads to congestion, resulting in an increase in local temperature, which can be detected through infrared thermography.

Table 1 Studies on the use of IRT in oncology

References	Research target	Research methods	Results
Liu et al. [12]	11,200 female outpatient or inpatient visits to our hospitals	IRT was performed and thermograms were recorded and analysed	150 confirmed breast cancer cases were detected, with 134 positive via IRT, yielding a 89.3% diagnostic rate. Among these, 83.5% were T4 grade. In 1384 benign cases, 82.8% were T3 grade. Of 9682 normal cases, 71.7% were T1 grade
Zhou et al. [13]	Convenience sampling selected 125 women from the outpatient clinic for the study	Infrared thermography, breast ultrasound, and mammography were conducted on study subjects' breast areas	Infrared thermography in the single-side breast area correlates positively with breast ultrasound ($r=0.739$) and X-ray mammography ($r=0.745$), with $P<0.05$
Godoy et al. [16]	The study included 102 adults, either those undergoing pathological testing or volunteers with benign diseases	Standardized DTI analysis was used to evaluate thermal images of actual patients in the study	The study found a statistically significant ability to distinguish benign from malignant skin diseases, with a sensitivity of 95% (CI 87.8–100.0%), specificity of 83% (CI 73.4–92.5%), and an AUC of 95%
Dong et al. [18]	90 patients with oral cancer and suspected cervical lymph node metastases	90 patients underwent neck infrared imaging; EGSVM-based infrared thermography was non-inferior to CT in efficacy	The automated EGSVM-based analysis had higher sensitivity (84.8% vs.71.7%), specificity (77.3% vs.72.7%) and accuracy (81.1% vs.72.7%), positive predictive value (79.6% vs.73.3%) and negative predictive value (82.9% vs.71.1%) than the manual qualitative analysis
Balasubramaniam et al. [19]	_	Reviewed infrared and indocyanine green images of CCH, choroidal metastases, and melanoma; main outcome was intratumoural choroidal vascular loops and bundles on infrared images	CCH vasculature showed dark beaded spaces on infrared imaging; 95.5% had vascular loops, compared to 65% in uveal melanomas and 64% in metastases. Sensitivity for CCH was 95.4%. Six patients exhibited peritumoural vascular dilatation on indocyanine green images
Chen et al. [20]	Eighty-eight patients with thyroid disorders, examined or consulted at our hospital, were randomly selected	Both colour Doppler ultrasound and medical infrared thermography were carried out on these patients, and the obtained results were then analyzed	Out of 88 patients with verified thyroid disorders, 36 had metabolic disorders and 12 had thyroid carcinoma. Color Doppler ultrasonography had a diagnostic rate of 79.5% (70/88), and medical infrared camera had 71.6% (63/88). There was no significant difference between the two methods ($P>0.05$). However, combining both methods achieved a diagnostic rate of 90.9% (80/88), which was significantly higher than using either alone ($P<0.05$)

Ferraris [21] utilised infrared thermography to investigate the association between periprosthetic tissue perfusion, mottling scores, and skin temperature in patients with septic shock. The study revealed that, despite the absence of a correlation between mottling scores and skin temperature, and the lack of predictive value for 28-day mortality, the presence of mottling was associated with a decrease in skin temperature. Conversely, another study highlighted a limitation of thermography, reporting its low sensitivity in detecting differences between methylprednisolone and placebo in terms of inflammatory response. This study used IRT to capture thermograms of patients 2 days after third molar extraction and found that the temperature difference between the two groups correlated weakly with swelling, with no statistically significant differences observed [22]. With the improvement of economic and medical standards, cesarean sections are increasingly common worldwide, leading to rising concerns about postoperative wound care and the prevention of surgical site infections [23]. In obese women, the risk of infection is higher compared to those with lower body mass. Studies suggest that IRT can be an effective tool for assessing infections [24], aiding clinicians in evaluating patients most likely to require antibiotics. If infrared thermography is employed in postoperative assessments following cesarean sections, it could enhance the management of infections, particularly in obese patients.

Specific studies related to the use of IRT in inflammation are listed in Table 2.

IRT in rheumatic diseases

IRT plays a pivotal role in the adjunctive assessment of rheumatic diseases, a group of clinical syndromes primarily characterized by joint pain, stiffness, and sensitivity to cold. Rheumatic diseases encompass a wide variety of conditions affecting bones, joints, muscles, and the surrounding soft tissues, including bursae, tendons, fascia, blood vessels, and nerves.

In evaluating the efficacy of non-steroidal anti-inflammatory drugs (NSAIDs) and steroidal anti-inflammatory drugs (SAIDs) in rheumatoid arthritis, some studies have shown that IRT can indirectly reflect the relationship between drug dosage and therapeutic efficacy by detecting changes in surface temperature. This offers an objective method for assessing the effectiveness of these medications [25]. Spalding [26] found a positive correlation between the degree of joint swelling, particularly in the finger joints, and the temperature observed in thermograms, with IRT demonstrating a diagnostic sensitivity of 67% for arthritis and 100% specificity in identifying arthritic swelling. Gatt [27] investigated whether patients with rheumatoid arthritis (RA) without active synovitis exhibited different baseline thermographic patterns in the fingers and palms compared to healthy controls. A comparison of data from 31 patients with RA and 51 healthy individuals, using infrared imaging of the region of interest (ROI), revealed that both finger and palm temperatures were significantly elevated in patients with RA without active inflammation. This research provides evidence that baseline thermal patterns in patients with RA differ from healthy individuals and suggests that IRT can

Table 2 Studies on the use of IRT in inflammation

References	Research target	Research methods	Results
Ferraris et al. [21]	46 patients admitted to the ICU for septic shock over 8 months were prospectively enrolled	Epidemiological data, hemodynamic parameters, mottling scores, and skin temperatures at five mottling sites around the knee were recorded using infrared thermography and FLIR™ software at admission to the intensive care unit (H0) and 6-h post-initial resuscitation (H6)	Knee skin temperature was significantly lower in patients with mottling (score ≥ 1) compared to those without (score 0), measuring 30.7 °C vs. 33.2 °C, with a *p* value of 0.01 at H6. Knee temperatures were similar across mottled groups 1 to 5 at both H0 and H6. Neither mottling score nor knee temperature correlated with 28-day mortality prognosis
Christensen et al. [22]	The study included 124 patients (67 males, 57 females, mean age 25) with 2 mandibular third molars needing extraction	A randomized crossover study was conducted with patients receiving either methylprednisolone or placebo. IRT and VAS scores for swelling were assessed on the second postoperative day. The outcome was temperature difference (Δt) between the surgical and control sides. Differences in Δt were analyzed with a two-sample *t* test, and Spearman's rank correlation was used for VAS swelling score vs. Δt correlation	No significant Δt difference was found between the methylprednisolone and placebo groups ($P = 0.07$). The VAS swelling score correlated with Δt at 0.30 ($P = 0.001$) after the first treatment and 0.09 ($P = 0.3$) after the second treatment

be a valuable tool in assessing disease activity in patients with RA.

Specific studies related to the use of IRT in rheumatic diseases are listed in Table 3.

IRT in painful disorders

The rapid advancement of IRT has significantly enhanced its application for detecting temperature variations across various body regions, as well as for establishing diagnostic criteria for diseases affecting different bodily systems [28]. Neck pain, a prevalent musculoskeletal disorder, lacks standardized treatment protocols, often resulting in substantial healthcare costs for patients [29]. Girasol et al. [30] demonstrated a negative correlation between the temperature of myofascial trigger points and electromyographic activity via IRT, suggesting that muscle activity increases during rest, thereby indicating the potential benefit of clinical interventions aimed at promoting muscle relaxation and enhancing blood circulation to manage musculoskeletal pain.

Liu study [31] with 59 herpes zoster patients investigated the link between IRT, Visual Analogue Scale (VAS) scores, and post-herpetic neuralgia (PHN) development. Thermography was performed at admission and discharge, noting temperature differences (ΔT). After 1 month, patients were split into PHN ($n=14$) and non-PHN ($n=45$) groups. There was no significant ΔT difference at admission, but a significant increase was found in the PHN group at discharge. VAS scores were also higher in the PHN group at both times. ROC curve analysis identified predictive thresholds for PHN: ΔT had an AUC of 0.814 with a threshold of 0.75 °C, and VAS scores had AUCs of 0.767 and 0.671 with thresholds of 4.5 and 2.5, respectively. The study concluded that infrared thermography is a more precise and objective method for early PHN prediction compared to VAS, highlighting its potential as a clinical diagnostic tool.

Li [32] observed that following intra-articular injection of tretinoin acetate in patients with gouty arthritis, the thermal image of the affected area displayed a marked reduction in the hot zone, offering direct evidence of IRT's ability to visually represent the extent of swelling and therapeutic relief.

Specific studies related to the use of IRT in painful disorders are listed in Table 4.

IRT in vascular-related diseases

Vascular diseases encompass a range of conditions, including inflammatory vascular diseases, atherosclerosis, and functional vascular disorders. At present, IRT is predominantly employed for diagnosing and monitoring peripheral vascular diseases, which refer to conditions affecting the peripheral circulatory system. These include varicose veins, thrombophlebitis, vasculitis, atherosclerotic occlusive disease, and Raynaud's phenomenon, among others. With the rapid advancement of economic and material conditions in recent years, the prevalence of peripheral vascular diseases has increased significantly, particularly in the context of diseases such as diabetic foot, which is commonly associated with diabetes

Table 3 Studies on the use of IRT in rheumatic diseases

References	Research target	Research methods	Results
Spalding et al. [26]	The study involved 18 wrists and 9 MCP regions from 17 arthritis patients and 10 wrists and MCP regions from 5 controls. HDI values from arthritis patients were compared to controls' data	A subset of 7 wrists and 6 MCP regions from 5 arthritis patients was used to develop and validate 3D imaging techniques. HDI values from 18 wrists and 9 MCP regions of 17 arthritis patients were compared with 10 wrists and MCP regions of 5 controls. Reliability was assessed with SD, CV, and ICC; both volume and SDI had CV < 1.3% and ICC > 0.99	Thermography showed HDI > 1.3 °C correlated with physician-assessed active arthritis ($r=0.68$, $p<0.0001$), with 100% specificity and 67% sensitivity compared to controls. While thermal measurements were less reliable than 3D, significant HDI differences were found between controls and arthritis patients. Two case studies showed quantifiable changes in swelling and temperature matched symptom and exam changes
Gatt et al. [27]	Data were collected from 31 patients diagnosed with rheumatoid arthritis (RA) and compared with that from 51 healthy controls	Medical thermography was employed to examine the regions of interest (ROIs)	Healthy participants had mean palm temperatures of 29.37 °C (SD 2.2, $n=306$) and finger temperatures of 27.16 °C (SD 3.2, $n=510$). RA patients had mean palm temperatures of 31.4 °C (SD 1.84, $n=186$) and finger temperatures of 30.22 °C (SD 2.4, $n=299$). A significant difference ($P=0.001$) was found, with RA patients having higher temperatures in all regions. Logistic regression confirmed significantly higher palm and finger temperatures in RA patients even without active inflammation

Table 4 Studies on the use of IRT in painful disorders

References	Research target	Research methods	Results
Girasol et al. [30]	40 chronic neck pain patients with myofascial trigger points in upper trapezius, aged 18–45	Single-blind cross-sectional study used numerical rating scale, Neck Disability Index, infrared thermography, arthrography, flexometry, and electromyography for assessment	Positive correlations found between right skin temp and cervical flexion ROM ($r = 0.322$, $P = 0.043$), right isometric median freq. ($r = 0.341$, $P = 0.032$), and left rest median freq. (rs = 0.427, $P = 0.032$). Negative correlation between right skin temp and right rest RMS (rs = −0.447, $P = 0.004$). Positive correlations also observed between left skin temp and right isometric median freq. ($r = 0.365$, $P = 0.020$) and left rest median freq. (rs = 0.573, $P < .001$)
Liu et al. [31]	59 patients with herpes zoster	Infrared thermography measured ΔT and VAS at admission and discharge in subjects, who were divided into PHN ($n = 14$) and non-PHN ($n = 45$) groups based on PHN development. The relationships between ΔT, VAS, and PHN at admission and discharge were analyzed. AUC and Jordon's index were calculated from the ROC curve to determine the predictive critical value	ΔT at admission was not significant between groups ($t = 0.665$, $P = 0.509$), but ΔT at discharge was higher in the PHN group ($t = 3.771$, $P = 0.000$). VAS scores were also higher in the PHN group at both admission ($t = 3.350$, $P = 0.001$) and discharge ($t = 2.076$, $P = 0.042$) ROC analysis for ΔT at discharge showed an AUC of 0.814, with a critical value of 0.75 °C for predicting PHN; 9 out of 14 cases with $\Delta T \geq 0.75$ °C had PHN. Admission VAS had an AUC of 0.767, with a critical value of 4.5; 10 out of 26 cases with VAS ≥ 4.5 had PHN. Discharge VAS had an AUC of 0.671 and a critical value of 2.5; 5 out of 9 cases with VAS ≥ 2.5 had PHN
Li et al. [32]	75 gouty arthritis patients randomized to lidocaine or trimethoprim groups	Infrared thermography and VAS scores were collected before and after treatment for statistical analysis	Post-treatment, VAS pain scores decreased in both groups, with the tretinoin group showing a significant reduction compared to the lidocaine group ($P < 0.05$). The trimethoprim group also had a significantly reduced temperature difference between the affected and healthy joints compared to the lidocaine group ($P < 0.05$)

Table 5 Studies on the use of IRT in vascular-related diseases

References	Research target	Research methods	Results
Ilo et al. [36]	Diabetics (118) and controls (93) in a controlled trial	Participants had ankle–brachial index, toe pressure, infrared thermography, and temperature measurements in five foot regions	Diabetic patients had higher foot temperatures and greater temperature differences between feet ($P < 0.001$) compared to controls. Temperature order: neuroischemic diabetics > neuropathic diabetics > vasculopathic diabetics. Abnormal TP patients (< 50 mmHg) had higher temperatures than those with normal TP (≥ 50 mmHg) ($P < 0.001$). Thermograms showed distinct patterns in hemangiomas, subclinical infections, and plantar hypertension areas

mellitus [33]. Diabetic patients often present with a combination of neuropathy and varying degrees of peripheral vascular disease, which significantly heightens the risk of complications such as infections, ulcers, and deep tissue damage in the lower limbs.

The application of IRT in the context of diabetes has garnered significant attention in recent years [34]. Selvarani [35] conducted IRT on the tongues of type I diabetic patients and found that the thermally active zone of the tongue before and after eating was larger in healthy individuals compared to those with type I diabetes. This suggests that infrared thermal imaging of the tongue could be a valuable tool for the early diagnosis of diabetes.

In a controlled study, Ilo [36] compared 118 diabetic patients with 93 healthy individuals, evaluating them using ankle brachial index, toe pressure (TP), IRT, and foot temperature assessments. The results demonstrated that diabetics exhibited significantly higher foot temperatures and greater temperature variations ($P<0.001$). Patients with neuroischemic diabetes had the highest temperatures, followed by those with neuropathy and vasculopathy. Patients with abnormal TP (<50 mmHg) exhibited higher mean foot temperatures compared to those with normal TP (≥50 mmHg) ($P<0.001$). Furthermore, the analysis of thermograms revealed distinctive patterns indicative of conditions such as haemangioma and subclinical infections. The study emphasises the potential of IRT as a clinical screening tool for detecting temperature changes in high-risk diabetic feet.

Specific studies related to the use of IRT in vascular-related diseases are listed in Table 5.

IRT in other diseases

IRT in respiratory diseases

Li et al. [37] implemented IRT during lung segmental resection to support surgical precision. By analysing the temperature variations displayed in thermograms, the researchers were able to define the boundary between ligated lung segments and healthy lung tissue. This innovative technique enables identification of the intersegmental plane necessary for performing lung surgery. Compared to traditional methods, the utilisation of IRT provides a safer and more user-friendly approach, reducing the complexity associated with determining intersegmental boundaries and improving precision. The application of this method offers significant potential to enhance both the safety and efficiency of lung segmental resection procedures. The adoption of IRT by surgeons is expected to result in more reliable outcomes, reduced risks, and the refinement of intersegmental plane identification in real-time during surgery. During the COVID-19 pandemic, a study utilized a portable infrared camera coupled with a smartphone to capture infrared thermograms of both patients with COVID-19 and non-infected individuals. The captured data were subsequently processed using advanced image analysis algorithms to classify lesions as either healthy or diseased [38], thus enhancing the efficiency of screening efforts.

Specific studies related to the use of IRT in respiratory diseases are listed in Table 6.

IRT in pregnancy

IRT also shows promise in the early diagnosis of pregnancy. As a woman enters pregnancy, physiological changes occur in the mammary glands, uterus, adnexa, and genital region, coupled with an increase in maternal metabolism and blood flow as the fetus grows. These alterations render infrared thermography a valuable tool for detecting pregnancy-related changes. Huang [39] performed infrared thermography on the pelvis and mammary glands of 50 non-pregnant women and 33 women with early intrauterine pregnancies. The results revealed significantly higher temperatures in the uterus, adnexa, and mammary glands of pregnant women, with the temperature difference between the high-temperature areas and surrounding skin also significantly greater than that in non-pregnant women. This diagnostic approach offers a safer and more cost-effective alternative for both the mother and fetus.

Topalidou et al. [40] conducted a pioneering study using IRT on ten healthy pregnant women from weeks 34 to 37 of gestation. The study concluded that IRT can identify the fetal head's position by detecting thermal patterns from fetal movements. This non-invasive method is appreciated for its comfort and safety in maternal–fetal monitoring, offering a visual understanding of fetal movement and interactions. IRT's contact-free observation of the fetus suggests a significant enhancement to prenatal care, complementing existing methods for safe and effective monitoring for both mother and child.

Specific studies related to the use of IRT in pregnancy are listed in Table 7.

Application of IRT in shock

In cases of shock, the effective circulating blood volume decreases drastically, resulting in insufficient tissue perfusion and a rapid reduction in body surface temperature. Ortiz-Dosal [41] observed that in children experiencing shock, distal temperature dropped by at least 7 °C compared to critically ill and healthy children without shock. This finding suggests that IRT could be an effective method for monitoring body temperature in critically ill patients, enabling clinicians to detect shock more promptly and intervene in a timely manner.

Specific studies related to the use of IRT in Shock are listed in Table 8.

Table 6 Studies on the use of IRT in respiratory diseases

References	Research Target	Research Methods	Results
Li et al. [37]	Applying IRT to lung segmental resection	–	Thermography shows temperature differences to identify lung surgery planes
Brzezinski et al. [38]	101 subjects in a study, mean age 56, 79% male. 61% tested virus-positive, 85% of those had lung injury	Upper back thermal images captured with a smartphone-connected camera. Extracted features: fractal dimension of the gradient (FD) and sum of the extremes (SX)	ROC curves showed FD and SX significantly associated with disease diagnosis, with AUCs of 0.85 (FD) and 0.82 (SX), both $P < 0.01$. Low FD (≤ 1.82) and/or SX (≤ 13.5) had 92% sensitivity and 62% specificity for disease status. FD and SX scores correlated with lung injury, with AUCs of 0.78 (FD) and 0.73 (SX), $P < 0.01$. Low FD and/or SX had 89% sensitivity but only 44% specificity for lung injury. For combined COVID-19 and lung injury diagnosis, FD (AUC 0.83) outperformed SX (AUC 0.79), both $P < 0.01$

Table 7 Studies on the use of IRT in pregnancy

References	Research target	Research methods	Results
Huang et al. [39]	The study included 50 healthy women and 33 women with early intrauterine pregnancy	Subjects underwent pelvic and breast infrared thermography	In early intrauterine pregnancy, women show mass-like high-temperature areas in the uterine region on infrared imaging, with an average temperature difference of 0.35 °C vs. 0.04 °C in non-pregnant women ($P < 0.01$). The adnexal region temperature difference is also higher in pregnant women at 0.39 °C vs. 0.26 °C ($P < 0.05$). Early pregnant women have a thermodrainage pattern in mammary thermograms, with a mean temperature difference of 0.63 °C vs. − 0.14 °C in non-pregnant women ($P < 0.01$)
Topalidou et al. [40]	Ten healthy pregnant women, aged 18–40, at 34–37-week gestation, with no significant medical history and English literacy, participated in the study. They had singleton pregnancies, viable fetuses, and pre-pregnancy BMI < 30	Infrared thermography was performed on the ROI from ASIS to the lower ribs	IRT can detect fetal head and movements create thermal patterns

IRT in burns

Internationally, burns are categorized into three degrees and four divisions based on the depth of the injury. First-degree burns involve only the superficial epidermis and generally do not count as part of the burned area in treatment. Superficial second-degree burns affect the superficial dermis, preserving some basal layer cells. Deep second-degree burns extend into the deeper dermis, with some remaining tissue in the dermal reticulum layer. Third-degree burns involve complete destruction of the skin layers and may extend to deeper structures such as muscles, bones, and internal organs. Currently, clinical examination methods for assessing the depth of superficial and deep burns exhibit certain limitations. Singer [42] utilized IRT to predict burn depth by recording infrared thermograms of burn patients on the first and second days post-injury. The study revealed that patients with non-deep burns exhibited a temperature increase of (1.5 ± 2.3 °C), whereas those with deep burns showed a decrease in temperature (− 1.5 ± 2.0 °C). A temperature decrease from day 1 to day 2 was indicative of a deep burn, while an increase signaled a non-deep burn. The diagnostic compliance rate for IRT was found to be significantly higher than that of clinical examinations, demonstrating that IRT provided a more accurate prediction of burn depth.

Specific studies related to the use of IRT in burns are listed in Table 9.

Table 8 Studies on the use of IRT in Shock

References	Research target	Research methods	Results
Ortiz-Dosal et al. [41]	Eight pediatric patients (five male, three female) aged 6–14 (mean 9.8) admitted to ICU	Control group: critically ill, stable children in ICU on ventilation/neuromonitoring. Second group: critically ill children in shock. Thermograms taken from wrist, dorsum of hand, and dorsum of foot per Glamorgan 10 protocol	In shocked patients, temperatures of the dorsum of the hand, dorsum of the foot, and wrist decreased. Non-shocked patients had normal temperatures similar to healthy children. Mean hand temperature was 25.98 °C (SD 1.38 °C) for shocked and 33.72 °C (SD 0.94 °C) for non-shocked patients, with a significant t value of −7.74 ($P < 0.005$). Mean foot temperature was 27.57 °C (SD 2.63 °C) for shocked and 33.11 °C (SD 0.92 °C) for non-shocked patients, with a significant t value of −4.99 ($P < 0.005$). Mean wrist temperature was 26.08 °C (SD 1.54 °C) for shocked and 33.58 °C (SD 2.37 °C) for non-shocked patients, with a significant t value of −5.13 ($P < 0.005$)

Table 9 Studies on the use of IRT in burns

References	Research target	Research methods	Results
Singer et al. [42]	39 cases of burns	IRT of burned skin on burn days 1 and 2	16 deep burns and 23 non-deep burns were recorded. Non-deep burns' mean temp rose from 30.6 ± 2.7 °C to 32.1 ± 3.0 °C (Δ1.5 ± 2.3 °C), while deep burns' mean temp fell from 32.3 ± 2.0 to 30.8 ± 1.3 °C (Δ− 1.5 ± 2.0 °C). Decreasing temp indicates deeper burns; increasing temp, less severe burns. IRTI accuracy was 87.2% (CI 71.8–95.2) vs. clinical assessment at 54.1% (CI 37.1–70.2)

IRT in autism

IRT has also been explored for diagnosing autism, a developmental brain disorder typically not associated with changes in body surface temperature. However, since individuals with autism spectrum disorders (ASD) often experience impairments in emotional processing, their facial skin temperature may differ from that of neurotypical individuals. The use of IRT allows for differentiation between children with autism [43] and those without, as well as facilitating the measurement of emotional responses.

Specific studies related to the use of IRT in autism are listed in Table 10.

IRT can be applied to certain diseases by detecting eye surface temperature

Thermal imaging of the face and tongue has emerged as a non-invasive, foundational screening tool [44, 45]. In an effort to deepen the understanding of the pathophysiology of glaucoma, several studies have employed thermography to measure ocular surface temperature (OST). The observed differences in OST between glaucomatous and healthy eyes lend support to the hypothesis of an underlying inflammatory process. These findings suggest that thermal imaging may serve as a basis for developing clinical biomarkers for glaucoma, although the prognostic significance of these biomarkers warrants further investigation [46]. In addition, OST is being explored in a study assessing its correlation with systemic risk factors for cardiovascular and ischemic heart diseases. Preliminary results indicate that individuals with a history of ischemic heart disease exhibit significantly higher OST across various ocular regions. The authors recommend further research to evaluate the potential of OST as a clinical screening tool [47] for these conditions.

The specific course of the study for the use of IRT in the detection of OST is shown in Table 11.

Limitations

Even though IRT is presently being employed in a number of clinical scenarios, it has not been integrated into diagnostic guidelines as of yet. Moreover, in line with the FDA's most recent pronouncement, it has not been acknowledged as a stand-alone medical technology. The utilization of thermography in many fields is still in the initial phase of development, and there are multiple obstacles that demand our attention and necessitate solutions.

Lack of harmonised standards

First, there is a lack of standardised technical parameters and test protocols, leading to variations in results depending on the manufacturer's equipment and the operator's expertise [48]. Second, there are no standardised requirements for environmental factors that can affect IRT measurements, such as temperature, humidity, airflow and room configuration. Third, there is still no agreed diagnostic framework for interpreting IRT results and many clinicians still rely on subjective or empirical judgement.

Influence of the subject's own factors

If a subject sweats or takes other measures to keep warm, the body surface temperature will change accordingly, with some effect on the thermogram. Normal physiological processes such as circadian rhythms, the menstrual cycle, age [49] and exercise can also cause changes in body surface temperature which, if not differentiated, can be mistaken for pathological changes. In addition, infrared radiation has a limited depth of penetration into body tissues, and areas with more fat or a more complex distribution of blood vessels can also confuse thermographic results.

Lower precision, specificity

IRT is not accurate enough to detect small or precisely located abnormalities, and can only show abnormalities in a specific area, which may result in certain microscopic lesions being missed [50]. The image of a particular abnormality detected by IRT is usually not specific to a particular disease or condition [51], and many different conditions produce similar thermograms, making differential diagnosis difficult. Imaging modalities such as X-rays, computed tomography (CT), magnetic resonance imaging (MRI) and ultrasound are far more advanced than IRT in terms of anatomical detail, tissue characteristics and diagnostic specificity, and as a result IRT currently plays a complementary role in the diagnosis of

Table 10 Studies on the use of IRT in autism

References	Research target	Research methods	Results
Ganesh et al. [43]	50 people with autism and 50 people without autism	Infrared thermal imaging measures facial temperatures (eyes, cheeks, forehead, nose), while audio–visual stimuli elicit emotions like happiness, anger, sadness	Anger showed the largest temperature differences between autistic and non-autistic subjects in the eye (1.9%), cheek (2.38%), and nose (12.6%). Classification accuracy for thermal images was 96% with custom neural networks and 90% with ResNet 50

Table 11 Studies on the use of IRT for OST measurement

References	Research target	Research methods	Results
Leshno et al. [46]	The study included 52 subjects (104 eyes): 25 with POAG, 27 with PXFG, and 66 control individuals	The Therm-App camera measures ocular surface temperature (OST) and records room and body temperatures. Advanced image processing software calculates mean temperatures of the medial uvula, lateral uvula, and cornea	OST in glaucoma patients was significantly higher than in controls (mean difference 0.9 ± 0.3 °C, $P < 0.005$), even after adjusting for age, gender, IOP, room temperature, and body temperature. Lens status and IOP-lowering medications had no significant effect on OST. POAG patients had higher OST than PXFG patients, but this was not statistically significant
Cohen et al. [47]	A cross-sectional study was conducted on 186 subjects	OST measured with Therm-App™ camera in medial, lateral, and central corneal regions. Room and body temperatures, medical and ocular histories, and clinical examination details were recorded	Thermograms from 150 subjects analyzed. Ischemic heart disease patients had higher OST in medial orbital, central corneal, and lateral orbital regions ($P = 0.02$, 0.02, 0.03). No OST differences in hypertension, diabetes, or smokers per ANOVA

disease rather than an alternative to these conventional imaging tests.

Future prospects and research directions

Only by addressing these challenges can the full potential of IRT be harnessed, paving the way for broader clinical applications. Future research should focus on improving the technology's accuracy, diagnostic specificity, and standardization while mitigating the effects of intrinsic and extrinsic environmental factors on test outcomes. For example, advancements are needed in the development of higher-resolution infrared cameras, precise calibration techniques, and enhanced image processing algorithms. As previously referenced in the literature, including the sections on skin cancer [16], head and neck cancer metastases [18] and the screening of COVD-19 [38], the employment of more advanced instruments and image analysis systems, equipped with sophisticated algorithms, has led to a substantial enhancement in the precision of IRT diagnosis. In addition, further studies are required to explore the disease-specific signatures visible on thermal images and to establish standardized diagnostic criteria.

In essence, while IRT serves as an alternative imaging technology, its significance lies in its ability to chart new diagnostic pathways by analyzing surface temperature variations—an area that remains under-explored for many diseases. By expanding the range of diagnostic options, simplifying disease assessment procedures, and enhancing diagnostic accuracy, IRT offers enormous benefits. Numerous publications on thermography underscore its advantages, particularly for low- and middle-income countries, as it is user-friendly, portable, and cost-efficient when compared to traditional diagnostic tools. Despite its current limitations, the potential of IRT as a clinical instrument for disease diagnosis and early detection is undeniable, warranting continued exploration and innovation in this field.

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Data availability
No datasets were generated or analysed during the current study.

Declarations

Ethics approval and consent to participate
Not applicable.

Competing interests
The authors declare no competing interests.

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