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SYSTEMATIC REVIEW

Beyond visual inspection: The value of infrared thermography in skin diseases, a scoping review

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Abstract

Although warmth is a key sign of inflammatory skin lesions, an objective assessment and follow-up of the temperature changes are rarely done in dermatology. The recent availability of accurate, sensitive and cost-effective thermography devices has made the implementation of thermography in clinical settings feasible. The aim of this scoping review is to summarize the evidence around the value and pitfalls of infrared thermography (IRT) when used in the dermatology clinic. A systematic literature search was done for original articles using IRT in skin disorders. The results concerning the potential of IRT for diagnosis, severity staging and monitoring of skin diseases were collected. The data on the sensitivity and specificity of IRT were extracted. Numerous studies have investigated IRT in various skin diseases, revealing its significant value in wound management, skin infections (e.g. cellulitis), vascular abnormalities and deep skin inflammation (e.g. hidradenitis suppurativa). For other dermatological applications such as the interpretation of intradermal and patch allergy testing, hyper–/anhidrosis, erythromelalgia, cold urticaria and lymph node metastases more complex calculations, provocation tests or active cooling procedures are required. Dermatologists should be aware of a learning curve of IRT and recognize factors contributing to false positive and false negative results. Nonetheless, enough evidence is available to recommend IRT as a supplement to the clinical evaluation for the diagnosis, severity and follow-up of several skin diseases.

INTRODUCTION

In dermatology, increased skin temperatures are mostly measured by physician's touch which is a crude and subjective assessment method. Medical professionals and lay individuals correctly identify 1°C differences only in 78% and 62% of cases, respectively.[1] Thermography captures infrared radiation emitted by objects or tissue and constructs an image using colour gradients that reflect warmer and colder areas. In recent years small, low-cost (200–600$) thermographic cameras have been developed, increasing the accessibility for clinical applications. Temperature differences of 0.1°C can be reliably detected. Two main procedures can be used, namely passive and active thermography (Figure 1). The latter includes cooling of the skin and monitoring of the rewarming phase. The aim of this scoping review is to provide the value and pitfalls of infrared thermography (IRT) when used in the dermatology clinic.

MATERIALS AND METHODS

A systematic search was conducted by two independent reviewers, R.S. and M.S. in Embase and Pubmed in June 2023. The following search query was used ("thermal imag*" or "thermography") and ("dermatolog*" or "skin" or "acne" or "rosacea" or "hidradenitis" or "wound" or "morphea" or "scleroderma" or "allergy" or "psoriasis" or "vitiligo" or "lichen" or "alopecia" or "cellulitis" or "fasciitis" or "herpes" or "fung*" or "osteomyelitis" or "melanoma" or "basal cell carcinoma" or "hemangioma" or "hyperhidrosis" or "anhydrosis" or "erythromelalgia" or "graft versus host" or

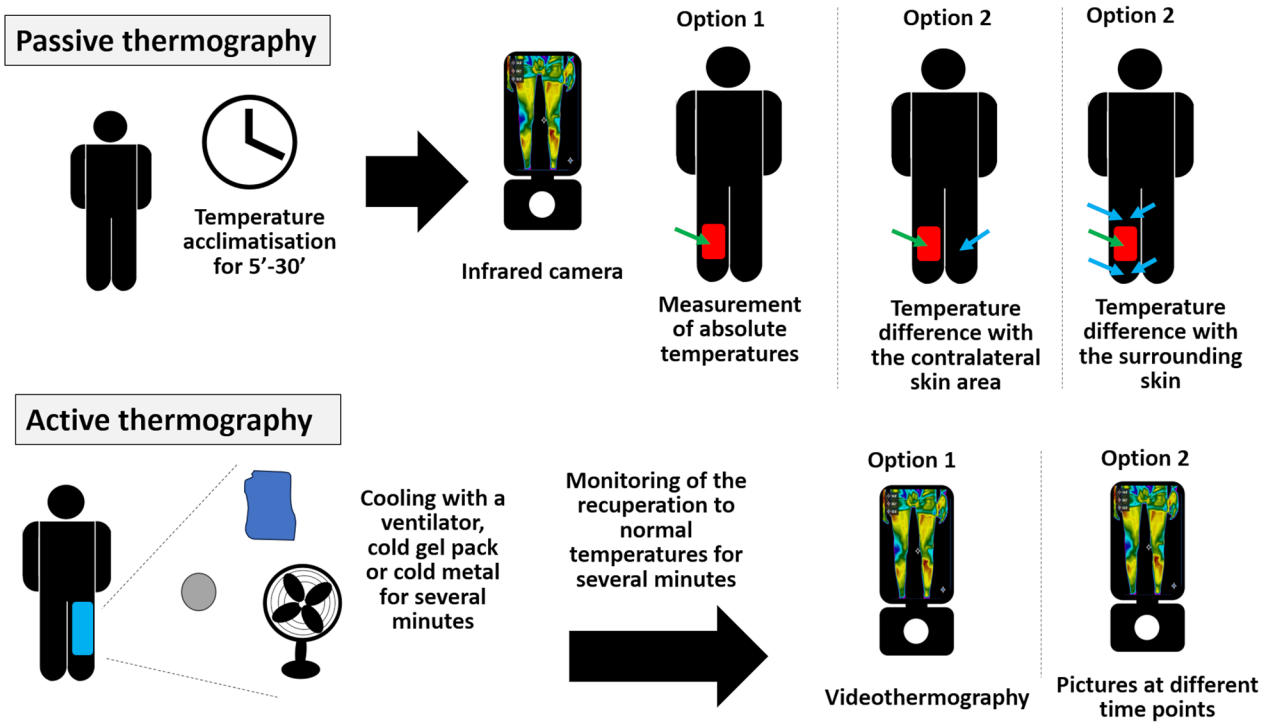

FIGURE 1 Passive and active thermography and the different measurement options. The first is a static method which involves a temperature acclimatization time of 5–30 min of the patient in the examination room. After acclimatization, a thermographic picture is taken. The analysis can be done based on the absolute temperature measured temperature of the affected area. However, in most cases a comparison with a surrounding of contralateral healthy skin area is preferred to reduce interindividual variations. These can come from intraindividual physiological differences or differences in the research environments (e.g. temperature in the room and humidity…).[69] The second method, also termed active thermography, includes cooling of the skin with cold gel packs, cold metal or immersion in cold water for several minutes. Subsequently, the rewarming phase is monitored by taking thermographic pictures at several time points. The advantage of this method is that more delicate pathological differences can be seen during the rewarming phase compared to steady-state analysis.

"urticaria"). All original articles on infrared thermography in skin disorders were included published between 1976 and June 2023. Papers on skin burns were considered outside the scope of this review. All article types including abstracts and reports in any language were included. The PRISMA flow diagram can be found in Figure 2. The results concerning the diagnosis, severity staging and monitoring of skin diseases were collected (Table 1). Data on the sensitivity and specificity of IRT were extracted. The cut-off points resulting in the highest sensitivity and specificity were summarized in Table 2.

RESULTS

In total, 256 articles were found on different type of skin disorders (Figure 3). Most articles were published on wound healing ($n = 59$), followed by infections ($n = 43$), skin cancer ($n = 36$), inflammatory skin disorders ($n = 26$), vascular-related disorders ($n = 25$), allergy ($n = 23$), skin sclerosis ($n = 17$), general dermatology ($n = 12$), hyper–/anhidrosis ($n = 8$) and other ($n = 7$).

Inflammatory skin disorders

Psoriasis

Psoriasis lesions exhibit higher temperatures than non-involved skin.[2] Nonetheless, hyperkeratotic psoriatic lesions can present as hypothermic.[3] In active lesions, increased temperatures often expand beyond the clinically visible psoriatic lesions. This left the authors speculating that the identification of increased temperatures beyond lesional skin is a sign of disease activity and these areas should be treated more aggressively.[4] IRT can follow the inflammation of psoriasis over time as a decrease in temperature is seen following successful treatment.[2]

Limited data are available on the identification of psoriatic arthritis by thermography. In a small study, large and small joints showed a reliable temperature increase compared to the surrounding skin.[5,6] The temperature in the axial joints correlated with the CRP levels.[5] After hand exercise, the temperature in inflammatory joints continues to decrease for a longer period compared to non-inflammatory joints and takes longer to recover to baseline values.[7]

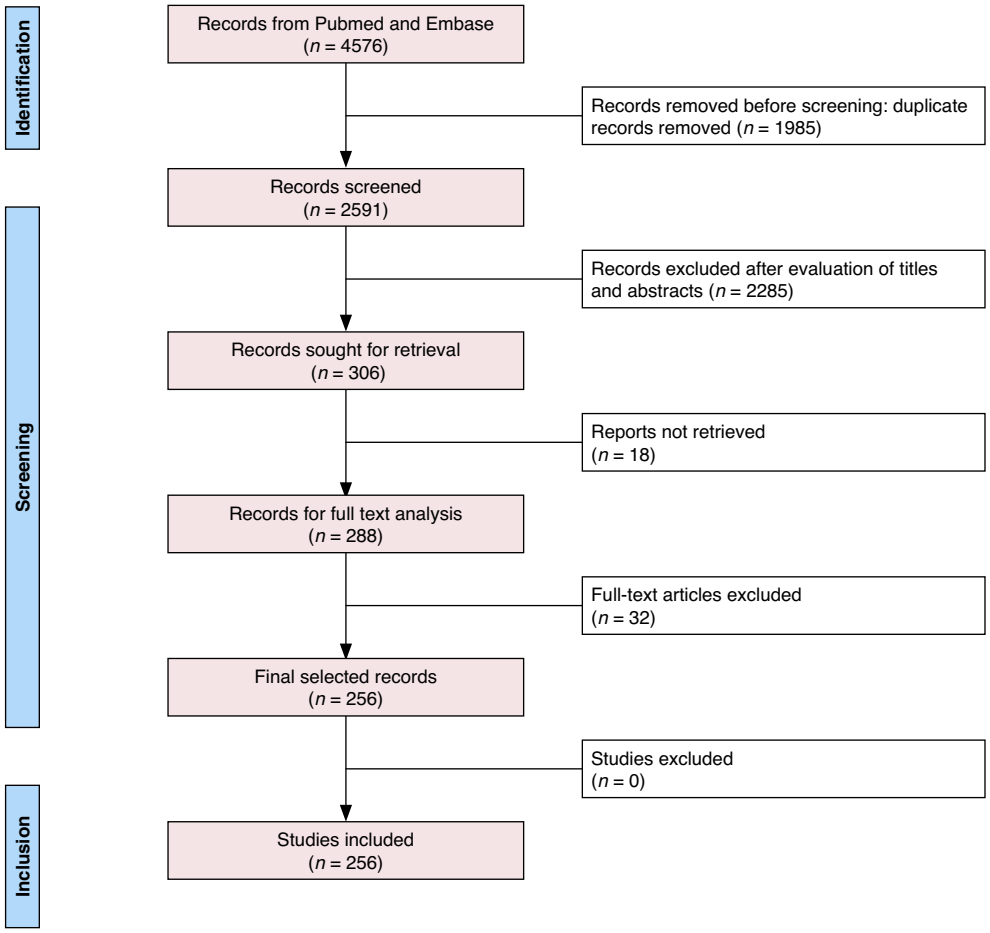

FIGURE 2 PRISMA flow chart.

Morphoea

In localized scleroderma, increased temperatures of the lesions are linked to disease activity.[8] Lesions can be considered positive when 0.5°C warmer than the surrounding area of the contralateral limb.[9] A crucial key for improving the accuracy of IRT is to identify subcutaneous fat atrophy by clinical inspection as this may result in false positives by IRT examination, especially on the face and the scalp. In some cases, active lesions do not display an increased temperature due to the oedema of the skin.[10] Excellent results have been reported in childhood linear scleroderma.[11] Decreases in skin temperature have been documented after successful treatment with methotrexate and mycophenolate mofetil.[12] IRT has been included as an assessment method in the consensus-based recommendations of juvenile localized scleroderma.[13]

Videothermography has also been tested in vulvar lichen sclerosus and was reproducible for the monitoring of the affected areas which are detected by cold areas due to sclerosis, although further validation is necessary.[14] Qu et al. found that active dynamic thermal imaging could correctly identify effective and ineffective treatments more adequately than hyperspectral imaging.[15]

Hidradenitis suppurativa (HS)

An obvious increase in skin temperature is visible in the centre of inflammatory hidradenitis suppurativa lesions (35–37°C) compared to healthy skin (33°C). Infrared thermography has been used to determine the tissue margins before surgical excision. It seems a promising biomarker for the assessment of the severity of inflammation in clinical practice and studies.[16] 'Hotspots' represent areas of active inflammation whereas 'coldspots' reflect discharge or open wounds. Coldspots can also be a sign of sinuses and tunnels in the subdermis.[17] Infrared thermography correlates with the HS staging severity and absolute hidradenitis suppurativa area and severity index (HASI) values. Excellent inter- and intrarater agreement was found. In some cases, visually mild disease can contrast with the presence of clear inflammation on thermal images. IRT

TABLE 1 Current value and feasibility of IRT for skin disorders.

Diagnosis	Value of IRT	Limitations
Accessible with limited knowledge		
Oral food allergy	• Increase in nasal temperature 20 min after allergen ingesting of 0.8°C points to food allergy[26] • Aerosol nasal administration with very limited amount of antigen and measurement of nasal temperature points to food allergy[27]	The temperature of the room should be controlled.
Infantile haemangiomas	• The extent of the lesion and involution can be more accurately assessed compared to visual inspection[68] • The growth of the haemangioma can be predicted (> vs <37.4°C)[68]	The difference with the contralateral healthy skin should be quantified.
Vascular malformations	• Differentiation high- versus low-flow vascular lesions by > vs <0.4°C[75]	The difference with healthy skin should be quantified.
Cellulitis	• Higher temperature increases points to cellulitis versus pseudocellulitis (more than 0.6–1.7°C)[35–37]	• Comparison with the contralateral healthy skin required • The sensitivity and specificity varies between studies
Herpes zoster	• A strong hyperthermic signal points to active inflammation[45] • Hypothermic areas suggest/predict postherpetic neuralgia[46]	The difference with the contralateral healthy skin should be quantified.
Tropical infections (tungiasis, Buruli ulcer, larva migrans)	• Infected areas show as clear hyperthermic areas[51]	Only information of the inflammatory areas is provided and no specific diagnosis
Osteomyelitis	• In diabetic feet, increased temperatures spreading to the ankle are suggestive of osteomyelitis.[51]	Gold standard imaging methods cannot be replaced
Basal cell carcinoma versus actinic keratosis	• Basal cell carcinoma has a cold pattern while actinic keratosis has a hot pattern[61]	Squamous cell carcinoma and melanoma have also a hyperthermic pattern
Hyperhidrosis and anhidrosis	• Hyperhidrosis displays cold areas whereas anhidrotic areas are hyperthermic[76,78]	Sweating should be induced by heat or exercise
Raynaud phenomenon	Diagnosis	Low sensitivity without cold challenge
Hidradenitis suppurativa	Quantification of disease severity[16]	• Sinuses and tunnels (=cold spots) • can be challenging • No differentiation from other types of inflammation
Pressure ulcers	• Increased temperature of periwound skin = better prognosis[81] • Lower periwound temperatures = inferior prognosis[81]	
Venous insufficiency	Varicose veins are clearly visible as hyperthermic areas	Inflammation presents also as hot spots
Venous, arterial and mixed ulcers versus neuropathic and pressure ulcers	• Venous, arterial and mixed ulcers = lower temperature[86] • Pressure and especially neuropathic ulcers = higher temperature[86]	Separation between venous and arterial ulcers is more challenging
Erythromelalgia	Objective method for diagnosis as other options are limited[9,100]	Flare should be provoked/present during the assessment
Glomus tumour	Good visualization of the glomus tumour[101]	The hand should be cooled for 15 min
Experience with interpreting IRT images needed or more complex calculation method		
Allergy patch testing	• Reliable differentiation of allergic from irritative tests[24] • Objective measurement that can be quantified	• Comparison with the surrounding skin needed • The back has substantial differences in temperature
Skin prick test	• Objective method to quantify skin prick testing[24,29,30] • Acceptable sensitivity and specificity	A formula calculates if the test is positive or negative or an automated model can be used
Psoriasis	• Hyperthermic areas extending the visual borders = progressive[4] • Evolution over time can be quantified • Limited evidence: screening for psoriasis arthritis.	Quantification of the extent of psoriasis is easier by visual inspection

TABLE 1 (Continued)

Diagnosis	Value of IRT	Limitations
Morphoea and linear scleroderma	• Disease activity can be assessed[8] • Skin atrophy can be visualized[10]	Inflammatory areas cannot be differentiated from skin atrophy. Correlation with clinical inspection needed.
Vulvar lichen sclerosis	• Thermography can identify sclerosis by hypothermic areas[14] • The response to treatments can be assessed[15]	Complex method using videothermography and an active cooling and rewarming phase
Fungal infections	• Lower toe temperatures are suggestive of tinea unguium.[49,50]	Other diagnosis of higher temperatures of the toe should be excluded (e.g. arthritis and pressure)
Melanoma metastases	• Detection of ≥1.5 cm melanoma metastases is reliable	Long reported screening time (14 min)
Lymph node metastases	• Detection of lymph node metastases can be done with decent reliability[65]	• Cooling with cold gel packs and monitoring of recovery • Both manual and automatic analyses published.
Acne	• Objective and quantifiable measure of disease activity[20]	• Acne lesions are not clearly seen as hotspots
Venous thrombosis	• Diagnosis and localization[99]	Differential diagnosis with venous insufficiency and earlier episode of thrombosis is challenging.
Peripheral arterial disease	• Diagnosis[85]	6 minute walk test with before and after measurements
Graft-versus-host disease	Early detection and follow-up[33]	Baseline thermography pictures before the patients develops graft-versus-host disease are rarely available.
Cold urticaria	Diagnosis[31,32]	Hand should be in cold water for 10 min with monitoring of the rewarming phase

can be of particular help to assess inflammation in patients with darker skin.[17]

In cases where extensive surgery is required for HS, IRT may supplement magnetic resonance imaging (MRI) as IRT can be done repeatedly during the procedure to confirm that all inflammatory lesions have been removed.[18] A limitation is that IRT primarily detects inflammation but cannot differentiate HS lesions from skin inflammation due to other causes.[19]

Acne/rosacea

In acne, the temperature of the affected area decreases with successful treatment and the homogeneity of the thermal area improves. IRT is therefore able to capture the severity of the acne.[20] IRT can be an objective quantitative assessment tool for detecting the efficacy of treatments, especially when visual impression is difficult.[20] No significant differences were found in skin temperature between erythematotelangiectatic rosacea, papulopustular rosacea and healthy controls.[21] However, significant differences were reported after the application of solutions with different lipid consistence. Temperature rises were also observed after laser treatment and alcohol ingestion.[22]

Allergy

Allergic reactions to patch testing are characterized by a hotspot extending beyond the borders of the patch site. A linear spread can be seen oriented towards the nearest lymph node. Irritative reactions display a hot zone restricted to the patch area.[23] The area under the curve (AUC) for differentiating allergic from irritative reactions is 0.850. IRT provides an objective, unbiased method for patch test reading.[24] Another study found also a strong correlation between IRT and the clinical reading although more true positive tests with thermography were identified (7.9% vs. 5.7%).[25]

IRT showed promising results for the diagnosis of food allergy. A temporary increase in nasal temperature was noted from 20 min after food ingestion showing excellent accuracy to predict symptoms. The median time for the first objective symptoms was 67 min, coinciding with a further rise in nasal temperature.[26] Peanut allergy was investigated by aerosol nasal administration of peanut protein. All 16 patients with known positive food challenge tests developed rhinitis symptoms and a significant change in nasal temperature compared to baseline. The mean nasal temperature increase was 0.9°C.[27] The protocol with only minimal amounts of antigen may prove valuable in cases of possible severe allergic reactions.

Thermographic assessment shows a good correlation with skin prick tests and serum IgE ($r = 0.76–0.99$).[28] The best results were obtained by performing the readings after 15 min. The sensitivity and specificity of IRT performed better for *P. pratense* and *D. pteronyssinus* than standard prick testing with a slightly decreased performance for cat epithelium.[29] A limitation of IRT was that skin areas with vascular traces should be avoided as effects of adjacent positive reactions may bleed over and vessels might influence the results.

TABLE 2 Sensitivity and specificity of IRT for skin disorders.

Author	Number of patients	Diagnosis	Aim	Sensitivity	Specificity
Allergy					
Rok et al. (2017)[28]	$N = 51$	Airborne allergens	Diagnosis by skin prick testing	72%–93%	60%–88%
Clark et al. (2007)[26]	$N = 24$ (13 pos.; 11 neg.)	Oral food (egg) allergy in children	Diagnosis	91%	100%
Hyperhidrosis					
Neema et al. (2021)[76]	$N = 55$ versus $N = 110$ ctrls	Palmar hyperhidrosis	Diagnosis and monitoring	98.2%–100%	94.5%–97.3%
Infections					
Hanumakka et al. (2021)[35]	Development: $n = 65$ versus 43 Validation: $n = 25$ versus 25	Cellulitis	Cellulitis versus pseudocellulitis	95.4%–100%	88%–90.7%
Ko et al. (2018)[37]	$N = 73$	Cellulitis	Cellulitis versus pseudocellulitis	96.6%	45.5%
Li et al. (2018)[39]	$N = 67$ ($n = 46$ vs. 21)	Cellulitis	Cellulitis versus pseudocellulitis	87.0%	38.1%
Raff et al. (2021)[36]	$N = 30$ ($N = 21$ vs. 9)	Cellulitis	Cellulitis versus pseudocellulitis	96.6%–100%	45.5%–50%
Anzengruber et al. (2019)[24]	$N = 126$ (420 erythematous lesions)	Contact allergy	Diagnosis by patch testing	84%	83%
Frykberg et al. (2017)[90]	$N = 129$ (37 pts; 53 ulcers)	Diabetic foot ulceration	Prediction	97%	43%
Miura et al. (2014)[49]	$N = 51$ (27 tinea; 24 without tinea)	Fungal infection in hyperkeratotic toes	Diagnosis	81.8%	65.7%
Kim et al. (2022)[46]	$N = 503$	Herpes zoster	Diagnosis of postherpetic neuralgia	80.7%	90.5%
Oe et al. (2013)[102]	$N = 20$ ($n = 10$ vs. $n = 10$)	Osteomyelitis	Diagnosis	60%	100%
Inflammatory skin diseases					
Tedesco et al. (2021)[14]	$N = 6$	Lichen sclerosis	Identify the effectivity of treatments	100%	100%
Ranosz-Janicka et al. (2019)[10]	104 lesions in 40 adults	Morphoea	Disease activity	80.7%	86.3%
Asada et al. (2003)[34]	$N = 22$	Palmoplantar pustulosis	Favourable outcome tonsillectomy	75.0%	83.3%
Birdi et al. (1992)[11]	18 lesions in 11 children (3 progressive)	Childhood linear scleroderma	Disease activity	100%	80%
Skin cancer					
Magalhaes et al. (2021)[63]	$N = 298$	Benign versus malignant skin lesions	Diagnosis	63%	58%
Magalhaes et al. (2019)[64]	$N = 46$ ($N = 16$ melanoma vs. $N = 30$ naevi)	Melanoma versus naevi	Diagnosis	91.3%	N.R. (Accuracy = 84.2)
Magalhaes et al. (2021)[63]	$N = 195$ (69 melanomas vs. 126 naevi)	Melanoma versus naevi	Diagnosis	94%	98%
Shada et al. (2013)[62]	$N = 74$ with 251 palpable lesions (≥1.5 cm: $n = 37$)	Melanoma metastases ≥1.5 cm	Diagnosis	98%–78%	89–100%
Vascular lesions					
Strumila et al. (2017)[73]	$N = 103$	Infantile haemangioma	Prediction of progression	75%	95%
Leñero-Bardallo et al. (2021)[75]	$N = 52$ (7 high-flow)	Vascular malformation	High-flow versus low-flow lesions	100%	100%

TABLE 2 (Continued)

Author	Number of patients	Diagnosis	Aim	Sensitivity	Specificity
Shaydakov et al. (2017)[99]	$N = 1405$	Venous thrombosis	Diagnosis	80%	70%
Wounds					
Lavery et al. (2019)[91]	$N = 129$ (37 patients with 53 ulcerations)	Diabetic foot ulceration	Prediction	Setting 1: 97% Setting 2: 80%	Setting 1: 33% Setting 2: 59%
Khandakar et al. (2022)[92]	$N = 122$ (diabetes), $N = 45$ (controls)	Diabetic feet	Severity of diabetic feet	95.09%	97.2%
Ilo et al. (2020)[85]	$N = 164$ versus $N = 93$	Peripheral arterial disease	Diagnosis	81.7%	65%
Raynaud phenomenon					
Cherkas et al. (2003)[97]	$N = 175$ versus $N = 404$ controls	Raynaud phenomenon	Diagnosis	11.5%	96%
Pauling et al. (2011)[98]	$N = 55$ ($N = 27$ vs. $N = 28$)	Raynaud versus systemic sclerosis	Differential diagnosis	85.7%	37%

Neumann et al. 2022 published an automated convolutional neural network approach using a thermal images with an AUC of 0.98.[30]

Cold urticaria

A difference in hand temperature has been found in patients with cold-induced urticaria following a cold-immersion test (hand in 10°C water for 5 min). 10 min after cold immersion, the regional temperature changes drastically. A more rapid tissue rewarming was observed in cold-induced urticaria which exceeded the baseline temperature at 15–30 min, especially on the palms. Cold-induced urticaria may therefore represent an overreactive protective response to cold where excessive mast cell degranulation induces vasodilatation.[31] The wheal-and-flare development after cold provocation can also be measured by IR,T and the efficacy of treatments can be quantified.[32]

Other

In frontal fibrosing alopecia, the accuracy of thermography is reported to be comparable to dermoscopic findings (erythema and perifollicular scaling). The combination of both techniques was most accurate to measure disease activity.[1] Diagnosis of cutaneous graft-versus-host disease after bone marrow transplantation remains an important problem. A preliminary study showed an increase in skin temperature on follow-up body thermograms.[33] In palmoplantar pustulosis, a raise in temperature of 1°C of the palms or soles 2–4 h after a 5 min tonsillar massage was linked to improvement of the palmoplantar pustulosis after tonsillectomy.[34]

Skin infections

Cellulitis and necrotizing fasciitis

Misdiagnosis of cellulitis at the emergency department is reported to be around 30%. IRT was tested as a tool to differentiate cellulitis from pseudocellulitis. The median temperature gradient was significantly higher in the cellulitis group with an area under the curve of 0.974. A temperature gradient of less than 0.4°C was strongly in favour of pseudocellulitis whereas more than 1.7°C difference resulted in a certain diagnosis of cellulitis.[35] Another study showed that the affected skin of cellulitis patients was 3.7°C warmer than the corresponding unaffected area whereas in pseudocellulitis patients only a 0.4°C difference was found.[36] The cut-off of 0.47°C seems most used with similar accuracy of around 87.5% in different studies.[37]

The accuracy of the teledermatology diagnosis of cellulitis versus pseudocellulitis based on history and photographs was 84%, which increased to 89% when thermal imaging

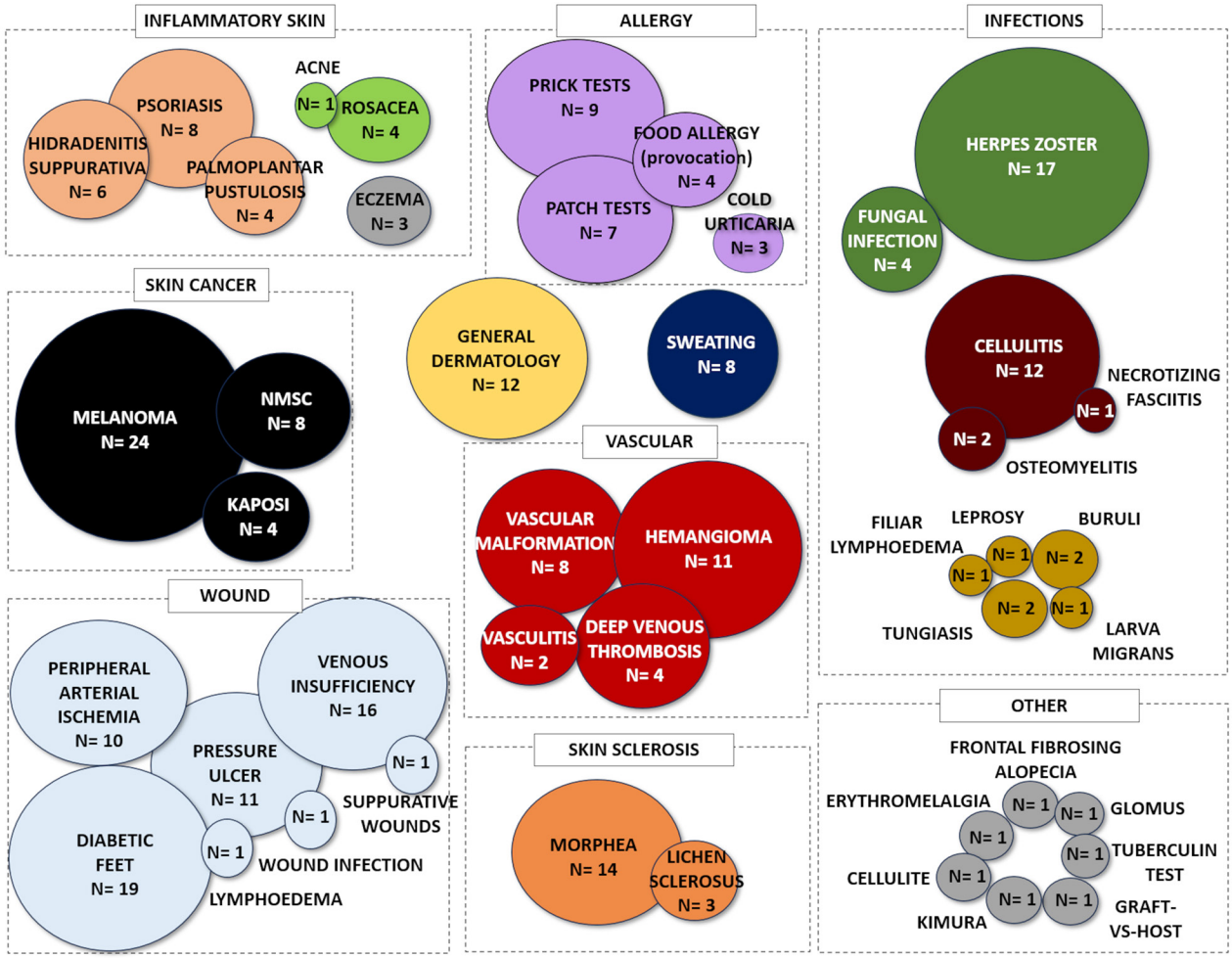

FIGURE 3 Number of articles on IRT in skin diseases.

was added.[38] In contrast, in a study of lower extremity cellulitis, the ALT-70 predictive model outperformed IRT.[39] IRT may be of particular value for the follow-up of patients with cellulitis. A gradual decrease in the infected area can be seen during treatment, even before the erythema improves. Additionally, necrotic tissue may become apparent which can only appear red and swollen. The heat can extend beyond the visible erythema in patients with progressive infections and improve faster than the erythematous area.[40] In necrotizing fasciitis, a fast progression in skin temperature and affected area is visible on IRT.[41]

Herpes zoster

In herpes zoster, a hyperthermic phase during acute inflammation can be followed by a normalization or a hypothermic image pointing towards neuropathy. Serial follow-up thermograms of herpes zoster showed a better correlation of the temperature difference between the affected and non-affected side and the visual analogue scale of pain than clinical inspection. There is conflicting evidence whether initial higher temperature differences are a risk factor for postherpetic neuralgic pain.[42–45] Nonetheless, intense and diffuse infrared emission might require for more aggressive treatment.[45] Kim et al. found in 503 herpes zoster patients that an equal or lower temperature of the herpes zoster area compared to the contralateral side at 12 weeks after the disease onset is a predictor of postherpetic neuralgia (AUC = 0.901; Table 2).[46] In herpes zoster ophtalmicus, the eyes present a similar pattern with an initial hotter pattern followed by a colder image, likely pointing to neuropathic damage compared to the contralateral eye.[47,48]

Fungal infections

In elderly with subungual hyperkeratosis, the mean toe temperature in patients with tinea unguium infection (30.2 ± 2.6°C) was significantly lower than in the non-tinea group (32.8 ± 3.2°C) with an optimal cut-off point of 33.0°C.[49] A similar study was conducted with younger participants (18–31 year) in asymptomatic onychomycosis showing a 2°C lower temperature in dermatophyte infection and 1°C lower temperature in yeast infection although the sample size was small.[50]

Tropical skin infections

In skin of colour, thermography can reveal inflammation which is clinically not obvious. The use of thermography

was reported in a Buruli ulcer where the extent of the lesion and associated lymphangitis was better revealed than with the naked eye. Although it does not allow for a specific diagnosis, tumours or cutaneous tuberculosis can be ruled out.[51]

The perilesional temperature in patients with tungiasis is increased compared to the median temperature of the affected foot. Correlations were found with the pain, the severity and the chronicity of the infection.[52] After removal, inflammation and hyperthermia regressed quickly. In case of challenging clinical inspections, IRT was able to identify the infection site.[53] Although larva migrans is primarily a clinical diagnosis, IRT detects the local increases in temperature to aid the diagnosis and follow-up. The minimum increase in heat was 0.4°C compared to the contralateral region.[54]

Lymphatic filariasis is often complicated by acute dermatolymphangioadenitis (ADLA). In 153 patients, IRT captured subclinical changes between no and mild lymphoedema, differences between moderate and severe cases and predicted progression. Increased heel and calf values were found in patients with a history of ADLA.[55] In leprosy, temperature asymmetry between the contralateral hand and foot indicates neural involvement.[56] IRT also reliably measures tuberculin skin tests. The mean temperature is higher in case of positive reactions (36.2 ± 1.1°C) compared to negative (35.1 ± 1.6°C), and the results correlate well with clinical inspection. A temperature increase of 0.5°C was observed with the surrounding skin area.[57]

Osteomyelitis

In patients with diabetic foot, an area of increased temperature extending to the ankle can be a sign of osteomyelitis. In case of severe angiopathy, this 'ankle pattern' may not be present.[58] Patients with chronic tibial osteomyelitis have an average temperature increase of more than 1°C. The authors conclude that IRT has significant potential as a complementary imaging modality although it cannot replace gold standard medical imaging such as MRI, CT or X-ray.[59] Thermographic imaging can aid in the differential diagnosis between ischaemia (cold spot) and osteomyelitis (hot spot) in scleroderma patients.[60]

Skin cancer

Basal cell carcinoma (BCC) displays a 'cold pattern' while actinic keratosis is characterized by an increased temperature. In one study, IRT outperformed dermoscopy for the differential diagnosis between BCC and actinic keratosis.[61] Higher temperatures are also observed in squamous cell carcinoma and melanoma. Melanoma shows a hyperthermic halo around the tumour which spreads towards the closest lymph node station (='comet' or 'thermal flame') compared to benign lesions such as dermatofibromas, cysts, seborrheic keratoses and scars.[62] Machine learning strategies showed good differentiation between melanoma versus nevi and melanoma versus non-melanoma lesions. Nonetheless, the general performance for differentiation of benign versus malignant lesions was low.[63] The latter is caused by the fact that melanomas are hotspots while nevi but also non-melanoma cancers are hypothermic.[63] Skin cooling for dynamic infrared thermography could increase IRT performance.[64]

Concerning the detection of nodal involvement, interesting studies have been performed in breast cancer.[65] IRT reached a sensitivity of 83% with a false negative rate of 16%. For the detection of metastatic lymph nodes, thermal analysis demonstrated superiority over ultrasound, mammography and magnetic resonance imaging.[65] For the detection of cervical lymph node metastasis, an automated analysis was non-inferior compared to contrast-enhanced CT.[66] Finally, Kaposi sarcoma lesions exhibits a 1.1°C higher temperature compared to the surrounding skin. This temperature difference decreases following treatment.[67]

Paediatrics

Haemangioma

Leñero-Bardallo et al. evaluated 55 patients with thermographic imaging. In 87.3% of cases, a temperature difference was found. During follow-up, the clinical assessment was in agreement between the reduction in peak temperature and extent determined by IRT. This indicates that the involution of infantile haemangiomas can be accurately measured by IRT.[68] Differentiation of lymphatic from vascular malformations is possible as a decrease in temperature is noted in lymphatic lesions.[69] A prospective study found a difference between haemangioma temperatures and the contralateral healthy skin of 1.9°F with a peak at 3 months of 2.5°F. A progressive decrease to 0.2°F was found at 18.5 months.[70] The involution scores on a VAS scale were inversely correlated with the difference in temperature. Infrared thermography may avoid unnecessary treatment of involuting haemangiomas and detect treatment failure. Temperature differences with the non-affected side correlate strongly with regressing haemangiomas on a systemic beta-blocker.[71]

The difference between the haemangioma temperature and the mean medial canthal temperature has also been proposed for objective comparison and monitoring of haemangioma activity.[72] A prospective study including 103 children with haemangiomas demonstrated higher median initial temperatures in growing haemangiomas (37.4°C) compared to slight growing (37°C) and stable haemangiomas (36.7°C). The temperature differences had an area under the curve of 0.929 for prediction of growth with an optimal cut-off temperature of 37.4°C. Haemangiomas of the extremities were excluded given the differences in temperature between the proximal and distal parts of the limbs.[73] The rewarming phase after cold exposure also reflects their activity.[74]

High-flow vascular malformations can be accurately differentiated from low-flow lesions. Temperature variations of 0.4°C were always present in high-flow vascular malformations. Low-flow lesions such as capillary malformations may also show increased temperature but always <0.25°C.[75]

Hyperhidrosis and anhidrosis

A study with 55 patients suffering from palmar hyperhidrosis and 110 controls resulted in an area under the curve of 0.995. A temperature difference of 11.5°F (and resp. 14°F) resulted in a sensitivity of 98.2% (resp. 100%) and specificity of 97.3% (resp. 94.5%) for the diagnosis of palmar hyperhidrosis.[76] A significant difference between mild 15 (±3.6)°F and severe 20.7 (±2.2)°F hyperhidrosis was found. The technique may also be useful for the follow-up of treatments.[77]

Anhidrotic or hypohidrotic areas are detected by hyperthermia by IRT, especially after induction methods for sweating such as heat or exercise.[78] Segmental or unilateral anhidrosis can be visualized clearly with IRT by a segmental increase in temperature.[79]

Wound healing

Pressure ulcers

Increased temperatures of skin around the wound compared to the wound itself are positively correlated to the healing of pressure ulcers.[80] This might be the result of re-epithelialization of full-thickness wounds. The authors concluded that IRT predicted the wound evolution better than clinical inspection. Another study confirmed the inferior prognosis of lower periwound temperatures by a higher risk of undermined wound borders in category III/IV or unstageable pressure ulcers.[81] A decrease in blood flow points to devitalized or necrotic tissue under the wound edges.

Venous, arterial and mixed ulcers

Mild chronic venous disease displays a local increased temperatures above 1.5°C whereas severe disease has areas of 2°C warmer than mild chronic venous disease with temperatures above 32°C representing varicose veins which are clearly visible. Deep varices, not visible by normal photography can be visualized.[82] A good correlation between the thermal imaging and duplex ultrasound parameters were found ($r = 0.63$).[83] Venous ulcers are 1.1–6.3°C colder than the periwound skin.[82] In contrast, higher temperatures of the wound site compared to the periwound skin may indicate critical bacterial colonization.[84]

IRT demonstrated decreased skin temperature in feet of patients with peripheral arterial disease compared to healthy controls. Nonetheless, no correlation was observed with the Ankle Brachial Index (ABI).[85] Another study did not detect temperature differences on the shin and the sole in patients with peripheral arterial disease compared to controls. Nonetheless, after a 6-minute walk test the temperature of the sole decreased in patients with peripheral arterial disease while increasing slightly in healthy controls. This temperature decrease correlated with the distance covered during the 6-min walk test and the ABI.[85]

When compared to the temperature of the contralateral normal region, venous ulcers, arterial ulcers and mixed ulcers have lower temperature while the temperature is increased in pressure ulcers and highest values are seen in neuropathic ulcers.[86]

Diabetic feet

Elevated temperature in diabetic feet points to inflammation, neuropathy and neuroischaemia and is predictive for ulceration, infection and eventually amputation.[87,88] A decreased temperature may indicate ischaemia.[89] A temperature difference of 2.22°C for two consecutive days between contralateral side can predict 97% of non-acute plantar diabetic foot ulcerations with a mean of 35 days before occurrence.[90] Monitoring one foot once daily can predict foot ulceration 41 days before clinical presentation.[91] Accurate machine learning models have been developed to classify the severity of diabetic feet.[92] An average ulcer temperature gradient of ≥1°C is an independent predictor of impaired healing.[93] A Finnish study predicts a potential 1.7 million euro annual savings by implementing IRT for diabetic feet.[94]

Raynaud

IRT can be used as a quick screening method for the presence of negative temperature gradients. In the case of Raynaud, the fingertips are cooler than the dorsum of the hand.[95] In most studies however, the diagnosis of Raynaud's syndrome by IRT included exposure to cold with assessment of the rewarming period. The hands of patients with Raynaud's syndrome take longer to rewarm. In contrast, structural vascular changes (e.g. systemic scleroderma) will not only prolong the rewarming period but the temperature recovery can also be incomplete.

When IRT was performed before and after a cold pressure test [immersion of hands up to the level of wrists into cold water (±9 degrees) for 5 min], a temperature >29°C before and <29°C 30 min after the cold pressure test was considered diagnostic for Raynaud's phenomenon. The authors concluded that the combination of a cold pressure test and IRT is good method for the diagnosis of Raynaud's phenomenon.[96] However, it has been suggested that in population setting, the cold challenge does not bring added value to the baseline assessment. Baseline pictures may even be better to differentiate between primary and secondary Raynaud's

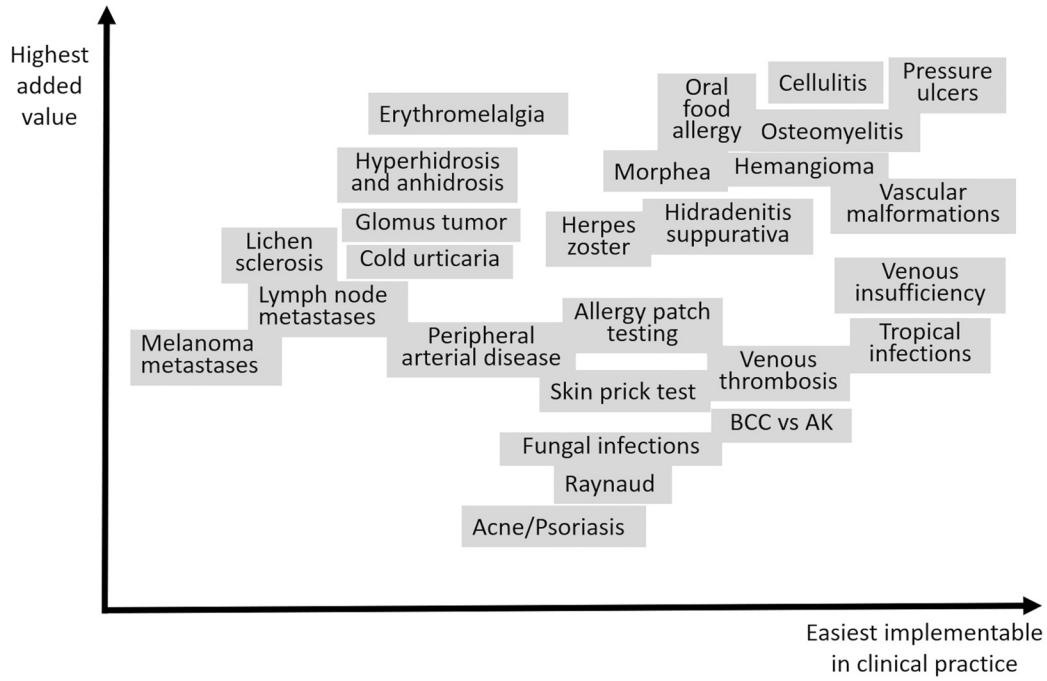

FIGURE 4 The clinical value and feasibility of thermography for different skin diseases.

phenomenon. However, although specificity of low baseline temperatures (≤24°C) is high (96%), the sensitivity is very low (11.5%).[97] For the differentiation between Raynaud phenomenon and systemic sclerosis, the sensitivity was excellent although with low specificity when any digit with one degree lower than the dorsal hand area was used as diagnostic criterion.[98]

Other non-inflammatory skin disorders

IRT has reasonable performance as an initial screening tool for thrombosis although the differential diagnosis with varices, superficial thrombophlebitis, lymphangitis, infection and muscle strain can be difficult, illustrating the need for duplex ultrasound.[99] After a DVT, the abnormal thermographic pattern can remain present in 65% patients with proximal DVT and 13% with distal DVT. This complicates the diagnosis of recurrent DVT.[99] An increased temperature in the affected skin can confirm erythromelalgia and IRT can also be used during follow-up.[9,100] The differential diagnosis of erythromelalgia includes complex regional pain syndrome (CRPS). Symptoms of CRPS are however often unilateral and can be proximal. CRPS can have both increased or decreased thermal skin areas.[100] Dynamic thermography was reported to be a good visualization method for glomus tumours on the hands and beneath the nails. A glomus tumour appears as a circular lesions beneath nails and can display a more indented pattern on the palm on the hand.[101]

CONCLUSION

A substantial amount of research has been done on thermography in skin disorders. Clear evidence of an added role of IRT for the diagnosis and monitoring of several disorders has been reported. For some diseases such as pressure ulcers, diabetic feet, cellulitis, osteomyelitis, infantile haemangiomas, vascular malformations, oral food allergy and hidradenitis suppurativa inclusion of thermography in the consultation can be done in seconds and provides meaningful information for the diagnosis, follow-up and treatment (Figure 4). Current IRT data support also its use in morphoea, herpes zoster, erythromelalgia, hyper–/anhidrosis, glomus tumours, cold urticaria, venous thrombosis and skin tumours. Inflammation invisible for the visual eye can be revealed while not all erythema corresponds to hotspots. Especially in skin of colour IRT can be useful to demonstrate inflammation. For other disorders, the added value is less clear as studies performed only a correlation with the standard practice which makes it difficult to estimate the added real-life benefit.

In conclusion, IRT offers some unique opportunities for the objective assessment of the temperature differences in a variety of skin conditions and can due its low-cost and feasibility easily be implemented in a dermatological consultation.

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CONFLICT OF INTEREST STATEMENT

None.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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