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The role of thermography in assessment of wounds. A scoping review

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ABSTRACT

Assessment of wounds based on visual appearance has poor inter- and intra-rater reliability and it is difficult to differentiate between inflammation and infection. Thermography is a user-friendly quantitative image technique that collects the skin surface temperature pattern of the wound area and immediately visualizes the temperatures as a rainbow coloured diagram. The aim of this scoping review is to map and summarize the existing evidence on how thermography has been used to assess signs of inflammation in humans and animals with surgical or traumatic wounds. The method follows the Joanna Briggs Institute methodology. The databases searched were PubMed, Embase, CINAHL and Cochrane Library. 3798 sources were identified, 2666 were screened on title and abstract, 99 on full text and 19 studies were included for review. We found that the literature is diverse and originates from a variety of scientific fields. Thermography has been used to detect and predict inflammation and infection in surgical wounds. Grading systems based on the visual appearance correlate to temperature patterns detected with thermography. The general tendency is that thermography detects the temperature in a wound with inflammation to be warmer than a reference area or the same skin area before surgery. In a surgical wound the temperature is elevated 1–2 weeks after surgery due to natural physiological inflammation that induces healing, after 2 weeks the temperature of the wound area slowly and steady decreases to baseline over 1–3 months. If a secondary temperature peak happens during the healing phase of a surgical wound, it is likely that infection has occurred. Modern handheld thermographic cameras might be a promising tool for the clinician to quickly quantify the temperature pattern of surgical wounds to distinguish between inflammation and infection. However, firm evidence supporting infection thermography surveillance of surgical wounds as a technique is missing.

Introduction

The bed-side clinical assessment of wounds using different scoring and grading systems based on visual appearance has generally shown poor inter- and intra-rater reliability [1–6]. For surgical patients with signs of infection, early treatment is warranted to prevent development of a deep infection. Often antibiotic treatment is initiated on suspicion or as a preventive measure which poses a risk of antibiotic overuse to prevent surgical site infection. A quick and reliable quantitative method for the differentiation between inflammation and infection in wounds is warranted [7–9].

Thermography is a quantitative image technique, that visualizes the skin temperature pattern by an infrared detector. Due to the rapid technical advancements and introduction of artificial intelligence software, the discipline of thermography is currently evolving rapidly [10]. The cameras are portable and user-friendly, with high resolution and accuracy [11,12]. With thermography we might now be able to measure and visualize the degree of inflammation and detect early signs of infection at a surgical site [10]. However, multiple factors influence the temperature measurements obtained with thermography. Environmental, individual, and technical details can impose a barrier to conducting trials and a risk to the interpretation of the results [13].

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Furthermore, thermography has never proven to be a concise and predictable diagnostic tool in evidence-based medicine [14,15]. Finally, previous research on how thermography has been used to assess wounds originates from many different scientific disciplines [15–17].

With this scoping review, we aim to map and summarize what has been reported on thermography used to assess signs of inflammation in humans and animals with surgical or traumatic wounds. Secondly, this review will investigate what has been reported on the correlation between thermography and clinical signs of inflammation in wounds especially in regard to what equipment has been used and how the measured temperatures have been extracted. Lastly, this review will identify which influencing factors have been addressed, how they affected the results and how the interpretation and experience with the influencing factors may impact the results.

Methods

Protocol and registration

This scoping review was conducted in accordance with the JBI (Joanna Briggs Institute) methodology for scoping reviews [18]. Reporting was in line with the Preferred Reporting Items for Systematic Reviews and Meta-Analysis extension for Scoping Reviews (PRISMA-ScR) [19]. The protocol was published prior to conducting the review on-line on Open Science Framework (OSF) [20]and additional material was later uploaded according to the iterative nature of the scoping review method.

All studies identified from diverse scientific fields investigating the assessment of inflammation using thermography in wounds, in humans or animals has been considered. The **Population** is both humans and animals. The **Concept** is clinical studies exploring thermography as an assessment tool to investigate wound inflammation. The **Context** was Peer reviewed papers from any scientific field.

Search strategy

An initial limited search in PubMed and Embase was conducted. Relevant text words and index terms were used to develop a more comprehensive search strategy based on the PCC (Population, Concept, Context) criteria. From a logic grid with key concepts, keywords and indexes a building block search strategy was designed with assistance from a librarian. To achieve a high recall/sensitivity rate, we implemented a broad search with a low precision rate [21], as advised in the Cochrane Handbook for Systematic Reviews of Interventions [22]. When suitable, we used controlled vocabulary terms (e.g.Medical Subject Headings (MeSH)) and free text words, combined with Boolean operators and truncations. No search limitations were added. The search strategy aimed to identify published and peer reviewed literature only. The databases searched were PubMed, Embase, CINAHL, and Cochrane Library. The first author conducted the literature search in collaboration with an experienced librarian (Primary March 16, 2022, Updated March 23, 2023). The reference list of all included sources of evidence was screened for missed additional relevant studies. Complete search string available in Appendix I. A source that revealed enormous numbers of citations, was the diverse nomenclature used in the literature referring to thermography (Appendix I). Examples include: Infrared thermography, Thermal imaging, Thermology, Infrared imaging, and Thermometry. This issue was further addressed by revising the eligibility criteria as follows: Only studies on non-contact infrared thermography published within the last 20 years and written in English were included.

Eligibility criteria

The inclusion criteria for study selection were (1) English language (2) Participants being human, or animals (3) Skin temperature assessed by non-contact infrared thermography, and (4) Studies investigating inflammation in wounds. The Exclusion criteria were: (1) Since the technology is rapidly developing and improving, if a study was published >20 years ago, (2) Conference papers and abstracts (3) Studies investigating other conditions than wounds (4) Wounds that originate from an underlying medical condition causing the wound; Example: venous ulcers or diabetes (5) Wounds caused by an excessive trauma; Example: Burn wounds. A complete list of exclusion reasons such as different wound type origin and conditions leading to development of wound has been listed Appendix II. The list of extended exclusion criteria was further developed during the title and abstract screening and the full text review. The list includes different medical conditions that we assumed would affect the inflammatory response and symptoms in the wound area, such as diabetes mellitus, inflammatory rheumatic, and dermatological conditions.

Since the literature on thermography originates from many different disciplines and traditions [17], only peer reviewed literature from the scientific field of evidence-based medicine and veterinary medicine was included. Clinical studies with all study designs were included, such as experimental studies, pilot studies, randomized controlled trials, non-randomized controlled trials, case control studies, cohort studies, and case series. All types of reviews and overview papers on the topic have been included during the title-abstract screening, for only a process of hand-searching the reference lists for relevant papers, but the review itself has not been included for mapping and data extraction.

Selection of sources

All identified citations were uploaded into EndNote (Clarivate Analytics, Philadelphia, Pennsylvania, USA), and duplicates were removed using the built-in software. The title-abstract and full text screening process was done using Covidence. A pilot test of source selection was done prior to the title abstract screening based on a random sample of 25 titles/abstracts. Three authors (MF, AB, SK) screened these papers using the eligibility criteria from the protocol and discussed discrepancies. Consensus modifications to the eligibility criteria were made, and only when 100 % agreement was achieved between the authors, did the screening process of titles/abstracts proceed. The eligibility of all included citations based on titles and abstracts were then screened by two independent reviewers (MF, AB) for assessment against the revised inclusion and exclusion criteria for the review. A third author (SK) sorted conflicts. During the full text screening relevant sources were retrieved in full text and their citation details were imported into Covidence. Two independent reviewers (MF, AB) assessed the full text of the selected citations against the inclusion criteria. Reasons for exclusion were recorded. Disagreements between the reviewers were resolved through discussion with a third reviewer (SK). The process is presented in Fig. 1 as Preferred Reporting Items for Systematic Reviews and Meta-analyses extension for scoping review (PRISMA-ScR) flow diagram [23].

Data charting process

Data was extracted from all 19 included papers by two reviewers (MF, AB) using a pre-designed data extraction tool. The original data extraction tool was published at OSF with the protocol and was refined and modified during a pilot session used on five randomly selected papers. Later, it was further modified in an iterative process during the data extraction by the reviewers and all modifications have been documented on OSF [20]. Specific details about the Participants, Concept, Context, study methods and key findings relevant to the review questions were extracted. No data meta-analysis was done, since the aim was to identify, map and summarize the existing knowledge and evidence. No quality assessment was done since that would violate the nature of the scoping review method.

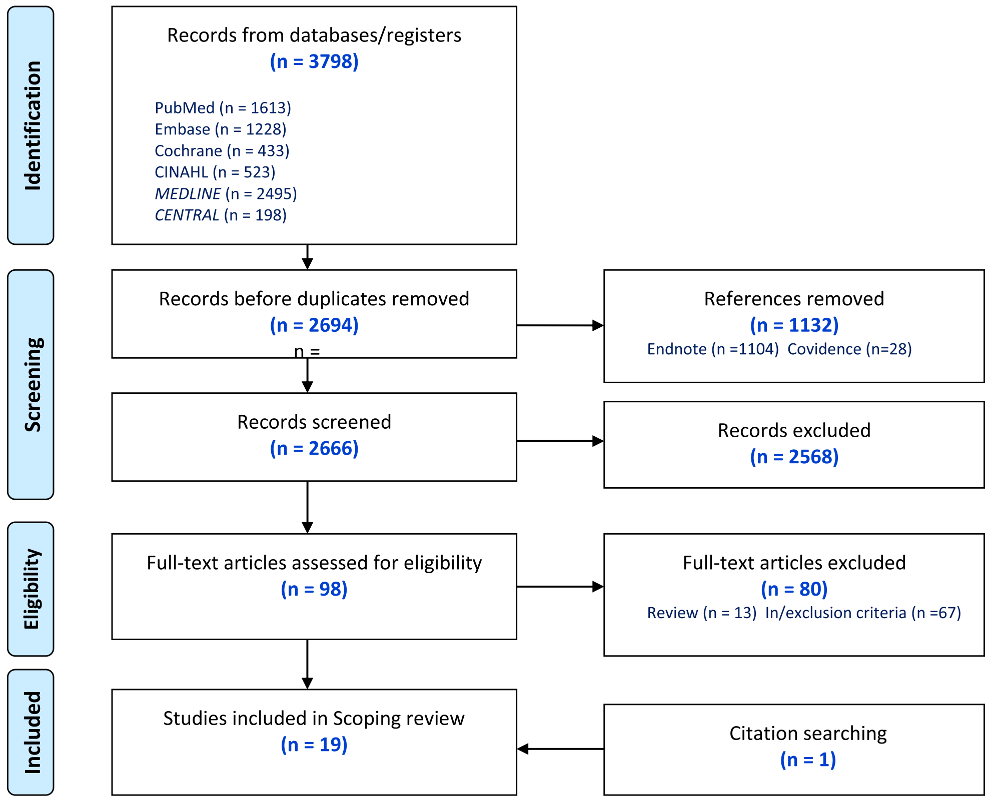

Fig. 1. PRISMA Flowchart illustrates search results and study selection process.

Synthesis of results

Data is summarized and presented as tables and figures in the result section. The sources are mapped according to the type of wound, signs of inflammation assessed, equipment used and influencing factors addressed. The methods for analysing the temperature patterns and main objective findings are presented and discussed. We have grouped the studies into the aim "what was the role of thermography" and specifically we have investigated the correlation between temperatures measured in the wound to clinical assessment (visual appearance).

Results

Selection of sources of evidence

The study selection process is illustrated as a PRISMA Flowchart, Fig. 1. We identified 3798 papers from the searched databases. In EndNote 1132 duplicates were identified. 2694 references were imported to Covidence. Additionally, 28 references were identified as duplicates and removed. In total 2666 studies were screened against eligibility criteria from title and abstract and during this step 2568 studies were excluded. In total 98 studies were assessed for full-text eligibility and of them 80 studies were excluded. Reason for exclusion: conference paper (13), reviews (13), not written in English (1), protocol (1), >20 years since publication (1), and not following the inclusion criteria (51) . The reference lists of all 13 reviews (that had been excluded) were hand searched for relevant studies not identified by our original search and 1 study was identified and included for full text review. In total, 19 studies were included for data extraction (Appendix III). No potentially relevant and not previously identified studies were revealed from hand-searching the reference list of all included sources.

Characteristics of sources of evidence

Settings identified during the full text screening were animal farm/feedlot/abattoir (3), veterinary hospital/research center (2), laboratory (2), community location (1), and hospital (12) (Table 1). Participants varied from 1 to 269 in each study, in total 773 individuals with wounds. Seven sources were animal studies and 11 were clinical studies on humans from various medical subspecialities. Four research groups had engineers involved in the work. Wound types were diverse with different anatomical locations, most of the wound types identified had a surgical origin (15 of the 19 included sources). Study designs varied from prospective cohort/observational (9), RCT (2), cross-sectional (2), proof of concept (2), case report (1), experimental (1), pilot (1) and retrospective (1). The included studies originated geographically from Europe (9), North America (5), South America (1), Asia-Pacific (4).

The aim of investigating temperature patterns in wounds and the role of thermography in each study is outlined in Table 1. It is important to note that the terminology used for inflammation in many sources is used broadly to describe phenomena and physiology such as healing, blood flow, metabolism, and infection. None of the studies applies strict criteria for inflammation. The terminology and vocabulary presented in Table 1,2,3 reflect the terminology for inflammation used in the original source in order not to violate the considerations and conclusion of each paper.

All studies used modern infrared cameras. All studies were performed under conditions consistent with standing next to a patient bedside in a clinical setting. The temperature used as outcome measure in each source is outlined in Fig. 2. 26 % used the maximum temperatures within a region of interest (ROI), either the wound or an area including the wound and the peri-wound area. 47 % used the mean temperature within the ROI, 16 % reported delta values (difference calculated, using a reference area), and 11 % of the sources are unclear in what temperature measurements are reported.

The influencing factors reported in all included sources have been

Table 1
Characteristics, setting, population and aim.

Study	Country	Design	Setting	Discipline	Wound type	Population	Participant Number	Aim and role of thermography
Scherer 2010	Germany	Prospective cohort	Laboratory	Anaesthesia	Surgical incision and subcutaneous injection	Animal	20	Study primary cold hyperalgesia after a surgical incision in mice
Fujita 2013	Japan	Case report	Hospital	Plastic surgery	Surgical	Human	1	Locate focus of infection. Demonstrate that detection of infection with a thermal camera is different from visible signs on digital photos.
Minniti 2014	USA	Cross-sectional cohort	Hospital	Haematology	Chronic leg ulcer	Human	18	Investigate temperature, blood flow, and histopathology in chronic leg ulcers in patients with Sickle cell anaemia.
Childs 2016	UK	A prospective feasibility and exploratory study	Hospital	Obstetrics	Elective caesarean section	Human	20	Develop and refine qualitative mapping and quantitative analysis techniques to define 'thermal territories' of the post-partum abdomen, the caesarean section site, and the infected surgical wound. Explore acceptance by patients with interviews (qualitative).
Kanazawa 2016	Japan	Pilot study	Hospital	Wound clinic	Diabetic foot ulcer and 3 Pressure ulcer	Human	8	Reliability and validity of FLIR One versus Thermography Tracer
Chanmugam 2017	USA	Retrospective Case Series	Hospital	Wound clinic	Surgical femur amputation and sacral pressure ulcer	Human	6	Detect inflammation/infection temperature changes in wounds compared to non-infected wounds in similar anatomical locations.
Marti 2017	Canada	RCT	Feedlot	Veterinary medicine	Surgical castration	Animal	48	Evaluate whether selected topical wound healing agents applied directly to the wound immediately after surgical castration, can it improve healing rate and reduce inflammation, secondary infection, and associated pain.
Lin 2018	Taiwan	Prospective randomized Double-blinded	Hospital	Orthopaedics	Surgical, total knee replacement	Human	102	Investigate if triclosan-coated (intervention) versus non-coated (control) sutures prevent surgical site infection. Outcomes are inflammatory markers, temperature, functional score.
VanDerSaag 2018	Australia	Randomized Controlled Trial	Farm	Veterinary medicine	Amputation dehorning	Animal	50	Assess the effects of a topical anaesthetic and buccal meloxicam (Mobic) on behaviour, maximum wound temperature, and wound morphology.
Yi 2018	USA	Experimental	Laboratory	Computer Science	Surgical, abdominal	Animal	12	Present a thermal imaging-based app and results from performance evaluation and validation. Investigate plasma with angiogenetic potential in wound healing.
Childs 2019	UK	Prospective observational	Hospital and Community	Obstetrics	Elective caesarean section	Human	50	Explore agreement in visual wound assessment between observers. Document the temporal infrared profile of the abdomen and during wound healing. Pilot study of performance and test-accuracy of infrared thermography signatures to predict later surgical site infection.
Siah 2019	UK	Prospective observational	Hospital	Colorectal surgery	Surgical, abdominal	Human	60	Detecting delayed wound healing by Infrared thermal patterns and temperatures at a surgical site for. Observing the abdominal skin surface temperature of non-infected and infected abdominal surgical

(*continued on next page*)

Table 1 (*continued*)

Study	Country	Design	Setting	Discipline	Wound type	Population	Participant Number	Aim and role of thermography
								wound sur in the first four days after surgery.
Marina 2020	Romania	Preliminary prospective study	Hospital	Plastic surgery	Mixed: traumatic lacerations, burns, limb trauma, necrosis, and diabetic foot	Human	12	Illustrate the possibilities of using a thermographic camera in the diagnosis and treatment of different wound types.
Teixeira 2020	Chile	Cross sectional - observational on a selected cohort	Abattoir	Veterinary medicine	Tail wounds from biting	Animal	269	Investigate the effect of tail lesion severity on skin temperature of slaughter pigs and the association between the temperature at the tail base and ear base using IRT. Investigate if the systemic inflammation and/or infection are associated with increased wound skin temperature.
Viscardi 2020	USA	Prospective observational cohort	Veterinary research centre	Veterinary medicine	Surgical, castration	Animal	33	Determine the ability of a CO2 surgical laser to reduce pain and improve wound healing of piglets undergoing surgical castration.
Proios 2021	Germany	Prospective cohort	Veterinary hospital	Veterinary medicine	Surgical, laparotomy	Animal	14	Verify the reliability of the palpation method to estimate elevated temperature under bovine practice conditions.
Rahbek 2021	Denmark	Explorative proof of concept study	Hospital	Orthopaedics	Surgical, pin sites	Human	13	Explore the capability and Intra-rater reliability of thermography in detecting pin site infection. Correlation between temperature and Modified Gordon Score.
Derwin 2022	Ireland	Prospective observational	Hospital	Wound clinic	Surgical, pilonidal sinus, traumatic, vascular ulcers	Human	26	Assess the effect of inflammation management on wound pH, temperature, and bacterial burden to develop a smart dressing.
Schollemann 2022	Switzerland	Proof of concept	Hospital	Anaesthesia	Chronic pressure injuries, acute laparotomy, and non-healing stomata	Human	11	Detect and predict infections in acute and chronic wounds and monitor wound healing using thermal data. A proof of concept test of the Image Probability Index.

divided into subgroups of individual (47 %), technical (68 %) and environmental (78 %) according to Fernandez Cuevas et al. [13] (Fig. 3). The reporting on influencing factors were in general very inconsistent. The most common environmental factor mentioned was room temperature and light settings in the room. All authors except one mention what specific type of infrared camera (brand/manufacturer), including the resolution and sensitivity of the camera used. Only 16 % reported on the emissivity setting on the camera, which is considered a fundamental issue in the discipline of thermography [13,15]. Thirty-seven% of the sources mention that they acclimatize after dressing removal or removal of clothes. <50 % of the human studies report on basic demographics and clinical data. Sixty-three% have measured the temperature of a reference area in addition to investigating the wound itself. Eleven% address reliability of study setup and temperature measurements.

The role of thermography in assessment of wounds

Thermography was used for detection of inflammation, prediction of inflammation (infection), or both. Twelve of the 19 included studies focused on **detecting** inflammation or infection, of those 5 used a clinical grading system to correlate the temperatures to the clinical visual appearance. Four out of 19 focused on **predicting** inflammation or infection, of those 3 used a clinical grading system to correlate findings with thermography to visual appearance. Three studies aimed **to both predict and detect**. The detection studies mainly used a specific temperature level or an interpretation of the findings on the thermograms as primary outcome, the prediction studies generally used a delta value, but not all studies had longitudinal data collection over time. The correlation between the temperature findings and the clinical assessment of inflammation is outlined in Table 2. The main findings are summarized below:

1. Wound temperature is elevated compared to a reference area (near or ipsilateral) (Chanmugam [24], Minniti [25], Childs [26,27])
2. A wound is warmer than the same intact skin area (non-wounded skin before surgery or healed wound) (Kanazawa [28], Lin [29], Scherer [30], Viscardi [31], Siah [32], Yi [33])
3. Inflammation and infection can be differentiated by temperature levels (Chanmugam [24], Rahbek [34], Childs [26,27], Teixeira [35], Van Der Saag [36], Derwin [37])
4. Early inflammatory biomarkers (IL-6 and ESR) follow the temperature pattern in a wound over time (3 month) (Lin [29])
5. The temperature of the wound (Infection probability index) correlates to CRP level in a serum sample (Schollemann 2022 [38])
6. Wounds have an acute inflammatory phase of 2 weeks, with peak temperatures within the first week (Marti [39],Van Der Saag [36], Viscardi [31])

Generally, the experience from these clinical studies is that wound temperature measured within the wound and the peri-wound area is

Table 2
Role of thermography; Prediction or detection – correlation to clinical assessment.

	Study	Thermography findings	Temperature level	Clinical assessment = Visual classification system	Correlation (Thermography <-> clinical assessment)	Detection or Prediction
DETECTION	Scherer 2010	Temperature rose 2 hours after incision. Decreased again over 6 hours. Inflammation had a steeper and longer temperature rise	Interpretation	Cold hyperalgesia Assumption: inflammation induction by injection	The incision had a weaker temperature response compared to injection “trauma”.	Detect inflammation
	Fujita 2013	Hot spot	Interpretation	Inflammatory markers, blood sample (CRP, Neutrophilic Leucocytes)	Detect location for infection	Detection of postoperative infection
	Minniti 2014	Wound bed (32,0 °C), Peri-wound (34.4 °C), Reference (mean 33,9 °C)	Specific	Flow in and around wound bed and histopathology	Peri-wound and wound region had elevated temperature and higher flow. Suggest an evaporative reason for cold wound bed.	Detection inflammation
	Kanazawa 2016	Wound bed warmer indicates inflammation	Interpretation	0	Reliability of two different cameras	Detect inflammation
	Chanmugam 2017	Wound temperature: Normal (+1,1-1,2 °C), Inflammation (+1,5-2,3 °C), Infection (+4-5 °C) in wound compared to the reference area	Specific	The diagnosis was set before thermography	The wound temperature was elevated compared to the reference area without a wound. Inflammation and infection had different temperature levels.	Detection of inflammation and infection
	Marti 2017	Inflammation measured using thermography	Interpretation	Wound healing score and pain score	The inflammation phase lasted 14 days after surgery. Healing occurred at day 35.	Detection of inflammation
	Lin 2018	Temperature rose from pre-operative (35.7 °C) to postoperative day 1 (36.9 °C). Temperature decreased gradually over 6 months to baseline.	Specific	Inflammatory blood test	Early inflammatory biomarkers (IL-6, ESR) follow temperature patterns over time (3 months)	Detection of inflammation
	Van DerSaag 2018	Wound temperature day 3 (40.4 °C) day7 (40.3 °C) day 1 (38.8 °C)	Specific	Wound morphology score	Day 3 and 7 showed higher temperatures compared with day 1, Reflecting the progression of inflammation.	Detection of inflammation
	Teixeira 2020	Score 0-1=32 °C, 2=35 °C, 3=36 °C, 4=37.1 °C) (Approximated from Fig. 3)	Specific	Tail lesions score	Increasing tail lesion severity was associated with increases in skin temperature measured at the base of the tail and ear	Detection of inflammation/ infection
	Rahbek 2021	Temperature at score 0=32.8 °C, 1=34.3 °C C, 2=34.8 °C, 3=36.1 °C. Variance with angle was 1.1 ºC	Specific	Modified Gordon Score	Temperature rises with rise in infection score. Cut off for infection 34 C	Detect infection
	Derwin 2022	Wound centre (32.6 °C), Peri wound (34 °C)	Specific	PH, Bacterial burden, wound size, Fluorescence light, TIME wound score	PH and Temperature decreased with wound size. Temperature increased with infection	Predict non healing. Infection detection
	Schollemann 2022	Infection probability index based on temperature findings	Delta	Grouped by wound type and CRP level above and below 100	Index correlates with CRP level	Infection detection
	Childs 2016	Temperature differences exceeded 2 °C in infected wounds compared to the reference area.	Delta	Centers for Disease Control criteria of surgical site infection by interview and patient chart data	Cold spots indicate a risk of infection. Delta T (= Reference minus wound site) exceeds 2C when infection.	Both prediction and detection of post-operative infection
DETECTION & PREDICTION	Marina 2020	0	Interpretation	0	Objectify vascularization, inflammation, and infection	Detection and prediction
	Yi 2018	Temperature decreased as the wound healed.	Delta	Wound Index and blood flow	A healing wound will have closer to 0 thermal index value than a non-healing wound	Track the healing trend.
PREDICTION	Childs 2019	Wound (+1.5 °C) warmer than reference area at day 2,7,15,30 after caesarean section	Delta	Centers for Disease Control criteria of surgical site infection by interview and patient chart data, visual infection risk grading	Infection risk if greater temperature gradient between wound and reference. Lack of agreement between raters grading	Infection prediction
	Siah 2019	Increase in wound temperature from day 1–4 after surgery	Delta	Centers for Disease Control criteria of surgical site infection by interview	“warming” pattern at incision is natural inflammatory healing at day 0-4. Cold spots indicate poor healing and infection risk	Prediction of delayed wound healing and infection
	Viscardi 2020	The temperature at the incision site was 2.8°C elevated 2 hours after surgery	Specific	wound score and Inflammatory blood test (Cortisol, prostaglandin, CRP)	Inflammation at surgical site decreased over time. No significant correlation to cortisol, prostaglandin, or CRP level	Detection of healing
	Proios 2021	Higher delta temperatures were seen with low ambient temperature	Delta	Back-hand palpation	Sensitivity in detection of hot area correlated with ambient temperature. Back hand method had low sensitivity.	Evaluation of infection screening tool

Table 3
Correlation between thermography and clinical signs of inflammation in wounds.

Author /pub year	Clinical assessment wound classification /Grading	Bedside or digital photos	Timing of assessment + thermography	Temperature findings in wound	Contribution to understanding
Derwin 2022	2 groups: Infected and Non-healing	Bedside	Thermography, pH, and clinical assessment were done 2 times in week 1 and 2 times in week 2.	w1 d 1 to w 2 d 4: Centre spot mean 32.6 °C -> 31.9 °C. Peri wound mean 34 °C ->33 °C. Mean wound bed Temp 32.7 °C -> 32.2 °C. Wound bed: decrease 1 %= 0,44 °C), Centre spot: decrease 2 %, and peri-wound decreased 3% over 2 weeks.	Findings indicate that an increased rise in pH and temperature pattern is indicative of bacterial burden and should raise concerns with the clinician. There was a strong positive correlation between temperature and wound size (r = 0.98). As pH and temperature decreased, wound size also decreased. Wounds went through a phase of slowly decreasing pH (alkaline) values until the wound was in the re-epithelization stage and almost closed, whereupon the pH returned to an acidic (normal) PH.
Marti 2017	A clinical state score (7 stages) and a Wound healing score (5 stages)	Bedside	Clinical assessment and thermography were done days −1,0,1,2,5,7, and weekly until day 49.	At day 49, the mean temperature (27.5–28.5 °C) and max temperature (32.6–33.8 °C) of wounds in all 4 groups. Until day 14 = inflammation, at day 35 healing.	Statement: During the inflammation phase, prevention of infection plays an important role in healing, as this phase persists as long as required to remove bacteria and exudate from the wound. (Until day 14 = inflammation, at day 35 healing). When infection occurs during the inflammation phase of the healing process, the wound may become chronic. Extended inflammation does not allow the proliferation and remodelling phase to proceed normally, thereby extending the healing time.
Rahbek 2021	Modified Gordon Score (0–6 scale)	Bedside	Thermography was done at the same session as MGS was done.	Mean temperature vary with MGS score: 0 (32.8 °C) 1(34.3 °C)2 (34.8 °C) 3(36.1 °C).	Max temperature at ROI (pin site area) temperature rises with MGS rise - cut off for infection 34 °C. Progression of infection represents a continuum from increased serous drainage over inflammatory redness to a stage with pus drainage or even fulminant osteomyelitis. Digital infrared thermography, by generating images of the thermal patterns of the patient's skin surface, provides qualitative and quantitative information on local inflammation.
Teixeira 2020	Tail lesions score (0–4 scale)	Digital Photos	Tail lesion score and thermography were both done on days 1,3,7 after surgery.	Score 0–1 = 32 °C, 2 = 35 °C, 3 = 36 °C, 4 = 37.1 °C) (Fig. 3). The temperature at the tail base was significantly lower for scores 0–1 than for all others. The temperature at the ear base was significantly lower for score 0–1 than for all others.	Increasing tail lesion severity was associated with increased skin temperature at the base of the tail (and the ear). After surgery, a natural inflammatory/healing pattern was seen. Higher skin temperature at the tail base indicates signs of inflammation and potential infection. Ear temperature rises as an indicator of systemic inflammatory response in animals with deep tail inflammation.
VanDerSaag 2018	Wound morphology score (1–3 scale)	Digital photos	Thermography and wound morphology scores were done on Days 1,3 and 7.	Max wound temperature on day 1 (38.8 °C), day 3 (40.4 °C), and day 7 (40,3 °C)	Significant effect of time (P = 0.003), with greater maximum wound temperatures on days 3 (40.43 ± 0.35 °C) and 7 (40.30 ± 0.40 °C) compared to day 1 (38.83 ± 0.42 °C). There was a significant effect of ambient temperature (P < 0.001). A moderate positive relationship between ambient temperature and maximum wound temperature was identified (R = 0.52). Wound morphology score decreased from day 1 to day 3, suggesting a reduction in inflammation as healing progressed. On day 7, temperatures rise, potentially reflecting the progression of inflammation due to infection because of flystrike.

elevated during healing and inflammation. The first 2 weeks after surgery the temperature is elevated due to the surgical trauma. If the temperature rises during the normal healing and inflammation phase where the temperature would decrease over time, it indicates infection has occurred. Studies focusing on prediction suggest that an area within or near the wound with "cold spots" equates to poor vascularization (especially in obese patients) and those wounds are at risk for surgical site infection and non-healing (Childs et al. 2016 [26] [40],and Yi et al. [33]) Liquid droplets/discharge on the wound surface will lead to vaporization and that phenomenon will be seen as a colder surface temperatures on a thermogram (Minniti et al. [25]), not to be misinterpreted as a “cold spot”.

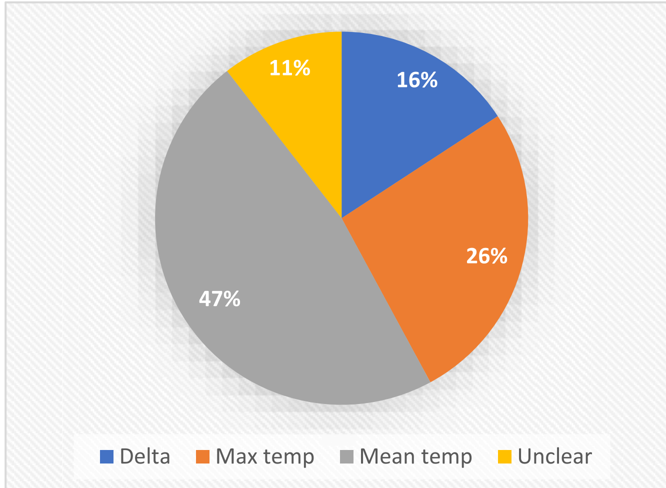

Fig. 2. Proportions of reported temperature measurement methods.

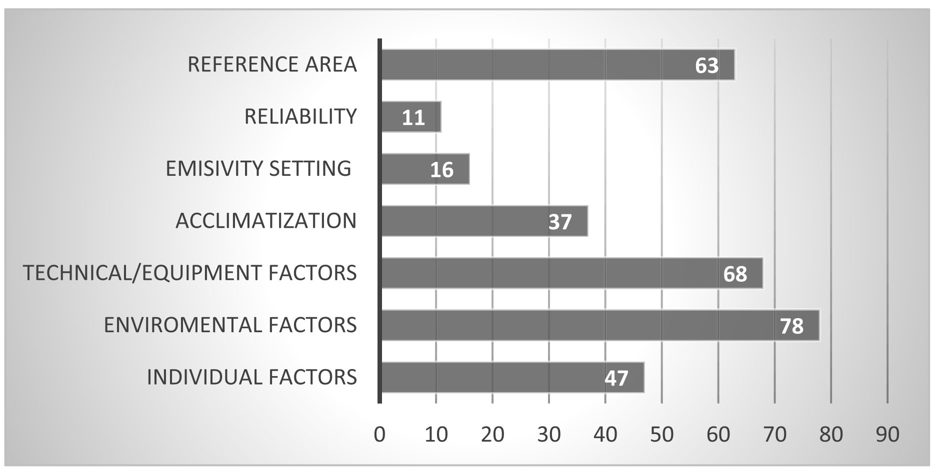

Fig. 3. Proportion of studies reporting various methods, reliability and influencing factors.

The correlation between the temperature in wounds and clinical assessments

To investigate the correlation between the temperature findings on the thermograms and the visual clinical assessment, 5 of 19 papers were selected based on the criteria: Have the temperature measurements of the wound been done at the same time as the clinical assessment was done? Information from these 5 papers is summarized in Table 3. Specifically, we have aimed to map the correlation between what has been objectified with thermography (the temperature measured in the wounds) and the clinical appearance. Since the studies have very different designs and methodologies, it's not possible to visualize a summary in a figure or report an average threshold value, but summarized to more general terms the sources in Table 3 are reporting the following correlation and trends:

Timeline The temperature within a surgical wound is elevated from day 0 to 14 due to normal non-infected inflammation (healing process). After 7–14 days, the temperature over 30–50 days normalizes as the wounds completely heal [39,36,31]. ***Wound size*** There is a correlation between wound size and temperature as the wound heals (decreases in size), the temperature decreases [37]. ***Peri-wound area*** The peri-wound area has an elevated temperature compared to the (central) wound bed [37]. ***Temperature level*** The measured at the wound area correlates to different clinical assessment gradings of healing and infection (visual appearance). If the clinical infection score rises, the temperature rises [34–36,39]. ***Bacterial burden and* pH *levels*** Bacterial burden and increased pH level correlates to elevated wound temperature[35,37]. ***Systemic temperature*** Systemic temperature rises due to general infection correlates to local wound temperature and the clinical assessment of infection (visual appearance) [35].

Discussion

This scoping review has explored the role of thermography in the assessment of surgical and traumatic wounds, by mapping and grouping the very diverse and explorative evidence available. Across diverse and explorative sources, we found a trend that wounds are warmer than non-injured skin and that this temperature rise is detectable with different modern thermographic cameras under pragmatic conditions (equal to bedside examination). This finding aligns with previously published literature where thermography has been used to assess burn wounds [12,41–46], diabetic foot complications and [47–50] other inflammatory conditions without wounds [14,51–54]. None of the included sources strictly followed or adhered to traditional guidelines for medical thermography [55–57]. In addition, the reporting is diverse with a variety of outcome measures and inconsistency in addressing reliability. We hypothesized, while deciding on the eligibility criteria for this review, that modern equipment can be used easily and reliably to assess wounds. Therefore, we only included literature published within the last 20 years and the trend seen in this review confirmed that decision [11, 12,58]. Modern cameras may also allow for a more practical examination set-up and less focus on influencing conditions in contrast to traditional guidelines for medical thermography which extensively address influencing factors that might not be applicable in a true clinical setting.

As a secondary outcome, we aimed to investigate the correlation between temperatures measured with thermography to clinical signs of inflammation in wounds. Our findings reveal that there seems to be a correlation, and this correlation was seen despite different scoring and grading systems used on several wound types in both human and animals. This is interesting because there is a lack of agreement among experts on the terms used to describe wounds in general and there is poor inter- and intra-rater reliability using different grading systems based on the visual appearance of wounds [1–5]. Current methods used to confirm ongoing wound infection and diagnostics tests for surgical site infection lack consensus, are time consuming and may delay treatment [51,59–61]. Thermography might be used for wound assessment or might be used as a point-of-care technology for home-based monitoring of wounds by patients in the future. However, further research is needed as this scoping review did not find evidence on how to use thermography as a bed-side diagnostic tool for wound infection detection.

Another pattern seen from mapping the available evidence is that a healing wound will, over time, normalize in temperature and if infection occurs in a wound during healing, the temperature will rise above the "inflammation level." In other words, sudden temperature elevation in a wound should raise concerns of infection. This trend aligns with the general understanding of when to suspect infection clinically, but from the available literature, it is still not possible to set a specific temperature threshold value to differentiate between inflammation and infection. We suggest that measurements of the same wound on the same anatomical location longitudinally over time might be the way to move medical thermography of wounds forward. By this method, the wound itself will serve as its own control and additionally we can avoid adjustment for factors such as underlying medical conditions, local anatomical issues, and other individual influencing factors [13].

Lastly, we would like to emphasize that detection of early wound infection may not be equally relevant to all wounds. This is because some chronic wounds might have a chronic infection of “harmless bacteria” and some wounds are never cleared from infection due to an underlying immune deficiency or vascular condition. After surgery, early infection detection is particularly desired. In orthopaedics a surgical site infection can lead to implant failure or a more catastrophic situation. The burden of surgical site infection to the healthcare system is critical (20 % of hospital-associated infections) [62] and solutions for home-based surveillance and care for surgical patients are warranted. We have chosen to focus on external fixator pin site infections for future clinical research within this field. Patients with external frames experience a high frequency of infection (50–100 %) and are closely followed in the outpatient clinic for 3–12 months. Pin sites have a small wound around the metal pins passing through the skin and they don’t heal due to the ongoing penetration of a metal pin through the wound. The clinical significance to detect early pin site infection to avoid further complications to the treatment with an external frame in orthopaedics such as a deep infection are relevant.

Though desirable, the very diverse nature of the literature included in this review precluded the ability to carry out a meta-analysis. No meta-analysis of the temperature measurements from wounds (773 participants) was done. However, mapping the trends and revealing the pattern of the use of thermography in wound assessment provides valuable insight into its potential role in clinical decision making and research. The strengths of this scoping review lie in the fact that it has been conducted in accordance with the JBI methodology and an extensive database search was conducted. A limitation to the scoping review methodology is that no critical appraisal of included sources is recommended to broaden the scope for explorative and diverse sources.

The evidence looks promising for using thermography as a surveillance tool to detect early signs of infection, and ultimately as an easy and quick diagnostic tool in the future. With large datasets and machine learning models using artificial intelligence pattern recognition, thermography might provide an objective measure of wound infection detection in the future.

Research ethics and patient consent

No ethics approval or patient consent was done before commencing this review, since this review includes only publicly published and peer reviewed sources.

CRediT authorship contribution statement

Marie Fridberg: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Anirejuoritse Bafor:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Christopher A. Iobst:** Writing – review & editing, Supervision, Conceptualization. **Britt Laugesen:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Jette Frost Jepsen:** . **Ole Rahbek:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization. **Søren Kold:** Writing – review & editing, Writing – original draft, Supervision, Resources, Project administration, Funding acquisition, Formal analysis, Conceptualization.

Declaration of competing interest

The Authors declares that there is no conflict of interest.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.injury.2024.111833.

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