Heliyon 10 (2024) e26806

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Research article

Smartphone-based thermography in flap surgery: A systematic review and meta-analysis of perforator identification

Loïc Van Dieren [a,b,c], Haïzam Oubari [a,b], Louise Callens [d], Yanis Berkane [a,b,e,f], Tom Quisenaerts [c], François Saget [g], Wiebren Tjalma [h], Gunther Steenackers [i], Curtis L. Cetrulo Jr [a,b,f], Alexandre G. Lellouch [a,b,f,*], Filip Thiessen EF [h,j,k]

[a] *Division of Plastic and Reconstructive Surgery, Massachusetts General Hospital, Harvard Medical School, Boston, MA, USA*
[b] *Vascularized Composite Allotransplantation Laboratory, Center for Transplantation Sciences, Massachusetts General Hospital, Harvard Medical School, Boston, MA, USA*
[c] *Faculty of Medicine and Health Sciences, Antwerp, Belgium*
[d] *Faculty of Medicine and Health Sciences, Ghent University, Ghent, Belgium*
[e] *Department of Plastic, Reconstructive and Aesthetic Surgery, Rennes University Hospital Center, Rennes, France*
[f] *Shriners Hospitals for Children, Harvard Medical School, Boston, MA, USA*
[g] *Department of SAMU-SMUR-Emergencies, Rennes University Hospital Center, Rennes, France*
[h] *Gynaecological Oncology Unit, Department of Obstetrics and Gynaecology, Multidisciplinary Breast Clinic, Antwerp University Hospital, University of Antwerp, Wilrijkstraat 10, B-2650, Antwerp, Belgium*
[i] *InViLab Research Group, Department Electromechanics, Faculty of Applied Engineering, University of Antwerp, Groenenborgerlaan 171, B-2020, Antwerpen, Belgium*
[j] *Department of Plastic, Reconstructive and Aesthetic Surgery, Multidisciplinary Breast Clinic, Antwerp University Hospital, Antwerp, Belgium*
[k] *Department of Plastic, Reconstructive and Aesthetic Surgery, Ziekenhuis Netwerk Antwerpen, Antwerp, Belgium*

ARTICLE INFO

Keywords:
Thermography
Free flap
Smartphone
Perforator detection
Perforator identification

ABSTRACT

Background: Thermography can be used in pre-operative planning of free perforator flap surgeries. Thermography assesses skin temperature by measuring the quantity of infrared radiation observed. In this meta-analysis, authors assess the sensitivity of smartphone-based thermal imaging (SBTI) in the detection of perforators and analyze the difference between static and dynamic imaging.
Materials and methods: Authors followed the PRISMA guidelines for systematic reviews and meta-analyses. The meta package in R was used to conduct the meta-analysis. The “metaprop” function was used to calculate the overall sensitivity estimate and 95% confidence interval. The “metaprop.one” function was used to calculate subgroup estimates for static and dynamic study types. The “metareg” function was used to conduct meta-regression analyses to explore sources of heterogeneity.
Results: This study includes seven articles with 1429 perforators being evaluated. The overall proportion of the sensitivities was estimated to be 0.8754 (95% CI: 0.7542; 0.9414) using a random effects model. The heterogeneity of the studies was high, as indicated by the tauˆ2 value of 1.2500 (95% CI: 0.4497; 8.4060) and the Iˆ2 value of 92.6% (95% CI: 88.1%; 95.4%). The pooled sensitivity for static imaging was 0.8636 (95%CI: 0.6238–0.9603) with a tauˆ2 of 2.0661 and a tau of 1.4374, while the pooled sensitivity for dynamic imaging was slightly higher (p = 0.7016) at 0.8993 (95%CI: 0.7412–0.9653) with a smaller tauˆ2 of 0.8403 and a tau of 0.9167.

* Corresponding author. MGH / Harvard Medical School, 50 Blossom St, Boston, MA, 02114, USA.
E-mail address: alellouch@mgb.org (A.G. Lellouch).

https://doi.org/10.1016/j.heliyon.2024.e26806
Received 30 October 2023; Received in revised form 14 February 2024; Accepted 20 February 2024
Available online 22 February 2024

Conclusion: Further studies need to confirm that SBTI is a reliable and convenient technique for detecting perforators for the pre-operative planning of free perforator flap surgeries.

1. Introduction

Free perforator flap reconstruction techniques are commonly used in reconstructive surgery. The success of such procedures depends on selecting the appropriate perforator. While pre-operative planning is not mandatory for performing free flap surgery, studies have demonstrated that it can decrease operative time, lower donor-site morbidity, and improve success rates [1]. Current methods for detecting perforators include Doppler ultrasound, computed tomography, or magnetic resonance angiography (CTA and MRA), indocyanine green (ICG) angiography [2,3]. ICG is an invasive technique that involves the use of a dye and a specialized near-infrared camera to detect its fluorescence. While ICG is highly accurate, it is also costly and time-consuming, exposing the patient to potential allergic reactions and other risks associated with injection procedures [4]. Doppler ultrasound is a non-invasive technique that uses sound waves to detect blood flow in the perforator vessels. However, Doppler ultrasound is highly operator-dependent, and the results can be affected by the patient's morphology and the location of the perforator vessels [5,6]. Additionally, Doppler ultrasound has a 45% chance of leading to a false-positive perforator detection [6]. CTA is the current gold standard for mapping perforators. It is a more advanced imaging technique using X-rays and contrast agents to make detailed images of the blood vessels. While it is highly accurate in detecting perforators, it is invasive and exposes the patient to ionizing radiation and potential allergic reactions. CTA is also costly and time-consuming, requiring specialized bulky equipment and trained personnel [7,8].

Due to the multiple limitations of the current imaging methods for the detection of perforators, there is a high demand for a cheap, non-invasive, and reliable tool. Therefore, smartphone-based thermal imaging (SBTI) has gained popularity recently for its benefits in detecting perforators. Thermography can be employed to assess skin temperature based on the quantity of infrared radiation observed [9]. This technique provides an indirect non-contact method of vascular imaging without the need for ionizing radiation or intravenous contrast. While high-resolution cameras typically cost tens of thousands of dollars, the FLIR ONE (Teledyne FLIR, Wilsonville, OR) is a smartphone-based thermal imaging camera that costs less than $250 [10,11]. The FLIR ONE possesses a thermal and digital camera that simultaneously takes photographs [12]. It uses a long-wave infrared sensor with a working temperature range of 0–100 °C, providing a thermogram displayed on the phone or tablet. Thermography can detect elevated temperatures on the skin's surface corresponding to areas with a higher concentration of heat dissipation from a dominant perforator. Over time, the imaging technique can portray the magnitude and extent of the vascular network surrounding the perforator, commonly known as the perforasome [9]. Although the FLIR ONE provides a lower resolution image and a narrower temperature detection range than more expensive thermal cameras, it has advantages such as a short learning curve and a simple point-and-shoot technology [13]. Other limitations of thermographic imaging include detecting surface information while not reporting any data on the origin or course of the vessel [2,14]. Some perforators can have an oblique trajectory towards the skin. This causes abdominal fat to insulate the heat of the initial segment, meaning that the hotspot will mostly correlate with the terminal segment of the perforator [8]. Hence, the perforator's caliber, origin, and path of that perforator will not be distinguished by SBTI. Moreover, thermal cameras designed for professional use are less likely to be affected by any thermal disruptions or anomalies in the background, such as the existence of superficial veins or areas of heat voids [15].

There is a conflicting opinion among experts regarding the effectiveness of SBTI in detecting perforators. Especially as regards the use of static or dynamic imaging. Static imaging involves capturing a single image of the area of interest, which can be done quickly and requires less expertise to perform. Static imaging is more efficient and less time-consuming than dynamic imaging [16]. However, proponents of dynamic imaging highlight its efficacy and effectiveness in identifying the location of perforators [17]. This is because dynamic imaging involves a cold challenge and capturing a series of images over time, which allows the surgeon to observe temperature changes. This might help detect the perforator's location more accurately than static imaging. Some studies have also shown that dynamic imaging can provide additional information unavailable with static imaging. For instance, dynamic imaging can help in identifying the direction of blood flow and detect variations in temperature gradients that are not visible in a static image [15].

Considering the conflicting opinions and the need for a more systematic approach to evaluating the effectiveness of smartphone-based thermal imaging, this systematic review and meta-analysis aimed to determine the sensitivity of the SBTI technology in detecting perforators. Furthermore, a subgroup analysis is conducted to compare the effectiveness of static and dynamic imaging in identifying perforators.

2. Methods

This systematic review was conducted accordingly to the PRISMA guidelines for systematic review and meta-analysis.

Data Sources and Search Strategy.

The search for relevant studies was conducted in February 2023, using the electronic databases PubMed (Medline) and Web of Science. The following MeSH terms were used to perform the search: Thermography AND Smartphone. Additionally, this study includes "FLIR ONE" in the search with the OR Boolean operator. Two independent reviewers searched, and any discrepancies were resolved through discussion.

2.1. Inclusion and exclusion criteria

Authors included all studies discussing the detection of perforators using SBTI in flap procedures. Other applications of SBTI, like flap monitoring, monitoring of burn depth or ulcer monitoring were excluded. For the quantitative meta-analysis, studies were included if they met the following criteria: reported sensitivity estimates and sample size, or true positive and false negative estimates; used a reference standard that was routinely used in flap surgery. No articles were excluded based on data or language. A proficient translator translated articles written in another language.

2.2. Data extraction

Two reviewers independently extracted data from each study using a standardized form. The following variables were extracted: study characteristics (author, year of publication, country, study design, sample size and patient population), diagnostic test characteristics (type of test and timing of test), sensitivity estimates (number of true positives, false negatives, and sensitivity), and measures of variability where applicable (standard error, confidence interval, or p-value). Additionally, the camera type, flap type, acclimatization time, distance from the camera to the target, room temperature, and cold challenge method were collected where appropriate.

2.3. Data analysis

Databases were managed using Excel (Microsoft Corporation, Redmond, WA, USA) and statistical analyses were performed using R studio software (1.1.463, available online). The meta package in R was used to conduct the meta-analysis. The "metaprop" function was used to calculate the overall sensitivity estimate and 95% confidence interval using the inverse variance method. The "metaprop. one" function was used to calculate subgroup estimates for static and dynamic study types. The "metareg" function was used to conduct meta-regression analyses to explore sources of heterogeneity, including study characteristics and diagnostic test characteristics.

2.4. Heterogeneity

Heterogeneity among the studies was assessed using the Q statistic and I^2 statistic. A random-effects model was used to account for potential sources of heterogeneity.

2.5. Risk of bias

The potential biases in the studies was assessed using the Quality Assessment of Diagnostic Accuracy Studies (QUADAS-c) tool, validated for evaluating the risk of bias and applicability concerns in diagnostic accuracy studies. This tool consists of four domains: patient selection, index test, reference standard, and flow and timing. Two reviewers independently assessed the methodological quality of each study, and any discrepancies were resolved through discussion or consultation with a third reviewer. The risk of bias and concerns regarding applicability were rated as "low," "high," or "unclear" based on predefined signaling questions for each domain. The results of the QUADAS-2 assessment were used to inform the overall quality of the evidence for this systematic review and meta-analysis.

3. Results

3.1. Overall results

The meta-analysis included seven studies with 1429 observations (Fig. 1). The term "observations" refers to the total number of data points or instances considered in the study. This encompasses the individual perforators that were detected and analyzed. Study characteristics can be found in Table 1. The overall proportion of the sensitivities was estimated to be 0.8754 (95% CI: 0.7542; 0.9414) using a random effects model (Fig. 2). The heterogeneity of the studies was high, as indicated by the tau^2 value of 1.2500 (95% CI: 0.4497; 8.4060) and the I^2 value of 92.6% (95% CI: 88.1%; 95.4%). This suggests that there was substantial variation in the effect sizes of the studies beyond what could be explained by chance alone. The Q statistic also indicated significant heterogeneity ($Q = 108.12$, $df = 8$, $p < 0.0001$).

3.2. Static vs. dynamic imaging

The analysis was stratified into static and dynamic imaging subgroups, with 5 and 4 studies, respectively. The pooled sensitivity for static imaging was 0.8636 (95%CI: 0.6238–0.9603) with a tau^2 of 2.0661 and a tau of 1.4374, while the pooled sensitivity for dynamic imaging was slightly higher at 0.8993 (95%CI: 0.7412–0.9653) with a smaller tau^2 of 0.8403 and a tau of 0.9167. The test for subgroup differences showed a non-significant result ($Q = 0.15$, $df = 1$, $p = 0.7016$), indicating no significant difference in the sensitivity of perforator detection between static and dynamic imaging modalities. However, it should be noted that the I^2 value for the static imaging subgroup was 95.8% compared to 77.5% for dynamic imaging, indicating a higher degree of heterogeneity within the static imaging subgroup.

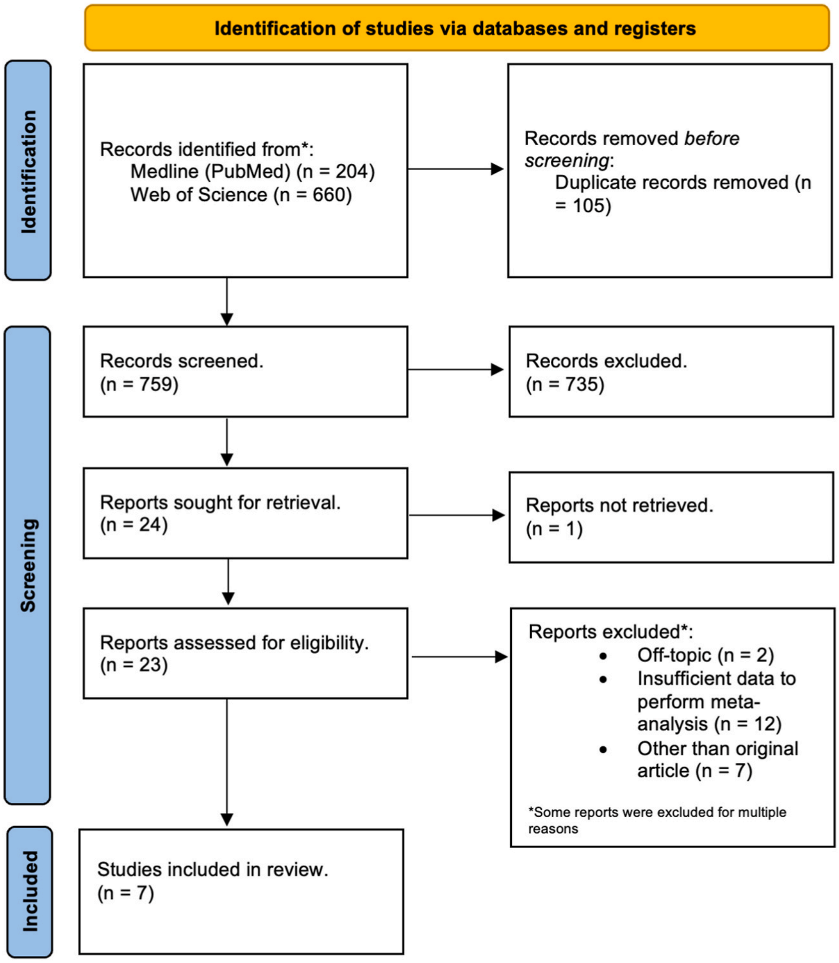

Fig. 1. Prisma flow diagram of search for articles.

Table 1
Characteristics of Included Studies.

Study	Dynamic vs Static Imaging	Camera	Number of Patients (n)	Location/Flap Type	Distance of Camera from Target	Acclimatization	Room Temperature	Cold Challenge	Comparison
Pereira, 2018	Static Imaging	FLIR ONE	20	Lower Extremities	70 cm	5 min	22 °C	N/A	CTA
Chen, 2019	Dynamic Imaging	FLIR ONE Pro	12	PAP Flaps	40 cm	3 min	26 °C	Cold Gel Pack (4 °C) for 15 min	CTA and IO exploration
Afzal, 2020	Dynamic Imaging	FLIR ONE	15	Lower Extremities	60 cm	1 min	22 °C	Ice Pack	Doppler and IO Exploration
Hennessy (1), 2020	Static Imaging	FLIR ONE	13	DIEP Flap	50 cm	3 min	22 °C	N/A	CTA
Hennessy (2), 2020	Static Imaging	FLIR ONE	13	DIEP Flap	50 cm	3 min	22 °C	N/A	Doppler
Obinah, 2020	Static Imaging	FLIR ONE Pro	13	ALT Flap	70 cm	5 min	23 °C	N/A	FLIR A35sc
Rabbani, 2020	Static Imaging	FLIR ONE	84	Upper limb, lower limb, abdomen, groin	Not specified	Not specified	Not specified	N/A	IO Exploration

(continued on next page)

Table 1 (*continued*)

Study	Dynamic vs Static Imaging	Camera	Number of Patients (n)	Location/Flap Type	Distance of Camera from Target	Acclimatization	Room Temperature	Cold Challenge	Comparison
Nischwitz (1), 2021	Dynamic Imaging	FLIR ONE	18	DIEP Flap	Not specified	Not specified	Not specified	Cool pack stored at 5 °C during 20 h applied during 20min	Handheld Doppler
Nischwitz (2), 2021	Dynamic Imaging	FLIR ONE	Not specified	DIEP Flap	Not specified	Not specified	Not specified	Cool pack stored at 5 °C during 20 h applied during 20min	Handheld Doppler

N/A: Not Applicable.
CTA: Computed Tomography Angiography.
IO: Intra-Operative.
DIEP: Deep Inferior Epigastric Perforator.
ALT: AnteroLateral Thigh.
PAP: Profunda Artery Perforator.

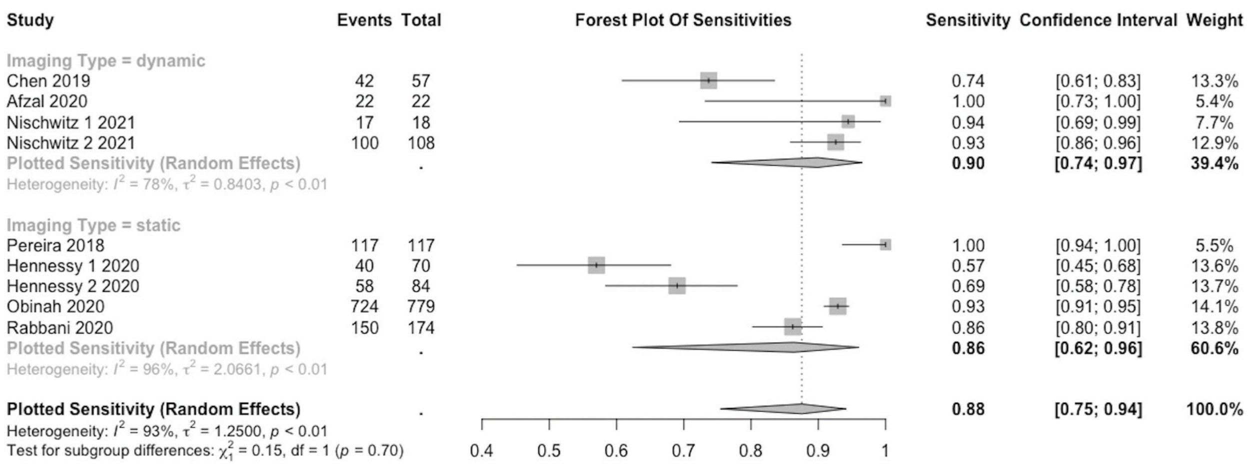

Fig. 2. Forest plot of included studies. Overall analysis of sensitivities shows a sensitivity for perforator detection using smartphone-based thermal imaging of 88% [95%CI: 75-94%]. Subgroup analysis show a statistical unsignificant difference between both subgroups with dynamic imaging being more sensitive than static imaging. High heterogeneity suggests a substantial variation in effect sizes between studies.

3.3. Risk of bias

Table 2 summarizes the risk of bias in the included studies using QUADAS-2, a tool for assessing the quality of diagnostic accuracy studies. The assessment is based on four domains: patient selection, index test, reference standard, and flow and timing.

Table 2
Table 2. Risk of bias of the included studies assessed by QUADAS-2.

	Risk of bias (QUADAS-2)				Applicability Concerns (QUADAS-2)		
	P	I	R	FT	P	I	R
Pereira, 2018	?	-	+	-	+	+	+
Chen, 2019	?	+	+	?	+	+	+
Afzal, 2020	?	+	+	?	+	+	+
Hennessy, 2020	?	-	-	-	+	+	+
Obinah, 2020	?	+	-	?	+	+	?
Rabbani, 2020	+	?	?	?	+	?	?
Nischwitz, 2021	+	+	+	?	+	+	+

4. Discussion

In 2016, Hardwicke et al. first assessed the use of a SBTI camera to detect perforators [11]. They found several abdominal cutaneous perforators and identified that the perforators of the anterolateral thigh (ALT) flap were in correspondence with anatomical landmarks. However, they only used acclimatization and not a cold challenge to detect perforators. Ko et al. replied to their article explaining their modified technology [13]. The cold challenge consisted of applying a cold towel, soaked in tap water at ±20 °C, to the area of interest. Rewarming made the visualization of hotspots much more obvious. They also found that quick heating in specific regions was a quality marker. The magnitude of the area experiencing this heating was linked to the quality of the vascular network. Moreover, hotspots that appeared first consistently correlated with both Doppler signal and CTA. By examining the extent of the heated region at the hotspot; dynamic imaging enabled the distinction of hotspots emerging concurrently [17]. However, according to Hardwicke et al. dynamic imaging (i.e involving a cold challenge) is not suitable for intra-operative use due to its prolonged operating time, potential for infectious complications, and discomfort for patients [16]. They stated: "A cold challenge may be better suited to the research environment rather than in preoperative, intraoperative, and postoperative settings [16]." Our experience within the context of perforator detection has been quite promising. We have found that integrating SBTI into our preoperative planning and intraoperative navigation processes has provided us with valuable insights and enhanced our ability to locate perforators accurately. While it's not a perfect solution, SBTI has demonstrated its potential to supplement our existing techniques and improve our surgical decision-making. It offers a convenient and accessible method for perforator mapping, particularly in settings where more advanced imaging modalities may not be suitable or readily available. While further research is needed to fully understand its limitations and refine its application, our initial experience suggests that SBTI could be a valuable adjunct in free flap surgery.

The meta-analysis, comprising seven studies and 1429 observations, indicates that the overall sensitivity of perforator detection is estimated to be 0.8754 (95% CI: 0.7542; 0.9414). This suggests that the methods employed in the studies were generally effective in identifying perforators and are comparable to other imaging modalities such as CTA and dynamic infrared thermography, as reported in a recent comparative analysis [18]. Specifically, the sensitivity of CTA was 93.87% whereas handheld Doppler showed lower sensitivity values of 69.02%. These findings are consistent with other studies that reported a sensitivity of 99% for CTA and 55.6% for Doppler [19,20]. In interpretation, the findings suggest that methods for perforator detection are generally sensitive, but the observed heterogeneity and identified biases raise concerns about the consistency and reliability of the results.

No significant difference was found between static and dynamic imaging, in the subgroup analysis. However, with a sensitivity of 0.8993 (95%CI: 0.7412–0.9653), dynamic imaging shows a slightly higher sensitivity compared to static imaging [0.8636 (95%CI: 0.6238–0.9603)]. These results contrast with the authors stating that dynamic imaging, especially using SBTI, is crucial to identifying perforators [21]. However, it is worth noting that some surgeons may strongly prefer dynamic imaging, mainly using SBTI, based on their clinical experience and expertise. Such clinicians may have found that dynamic imaging helps them better visualize the blood flow dynamics and identify the precise location of perforators. It can be challenging to contradict the claims of these experienced surgeons without conducting a more extensive study with a larger patient cohort. Moreover, using SBTI for perforator identification is a relatively new technique, and there is still much to learn about its optimal use in clinical practice. Therefore, further research is needed to explore more optimal imaging modalities for identifying perforators in various clinical scenarios.

The presented work has several limitations that should be considered when interpreting its findings. Firstly, the meta-analysis only includes seven studies, which may need to be more representative. The limited number of studies included may also limit the applicability of the findings to other populations or settings. Secondly, the high heterogeneity observed among the studies included in the meta-analysis (Iˆ2 = 92.6%) suggests a substantial variation in effect sizes between studies, which may impact the precision and accuracy of the overall estimate. Thirdly, while the meta-analysis used a random-effects model to account for heterogeneity, it is still possible that unmeasured confounding factors or biases may have affected the results. The risk of bias assessment shows that the quality of the evidence from the included studies may be limited. Finally, the meta-analysis used logit transformation and continuity correction, which may affect the precision of the estimated effect size and confidence intervals. These transformations can also make it challenging to interpret the clinical significance of the findings.

Regardless of the study's limitations, SBTI can become a valuable complementary tool to CTA for locating perforators. Where a quick perforator detection is necessary or when a contra-indication for IV contrast and/or radiation exists, SBTI can potentially replace handheld Doppler as a diagnostic tool for locating perforators. Moreover, SBTI has some unique advantages over other imaging modalities. It is non-invasive and does not require the injection of contrast agents or exposure to ionizing radiation. It is also intuitive, the learning curve is short, and is minimally operator dependent. Finally, SBTI can be combined with other imaging modalities, such as CTA, to improve the accuracy of perforator detection and preoperative planning.

5. Conclusion

This study adds to the existing body of evidence supporting the use of SBTI to identify perforators. Additionally, further studies are needed to confirm that SBTI is a reliable and convenient technique for detecting perforators and can be used as an alternative to a handheld Doppler or in conjunction with CTA for preoperative planning of perforator flaps. It highlights the need for further research to explore the optimal imaging technique for preoperative planning of perforator flaps.

CRediT authorship contribution statement

Loïc Van Dieren: Writing – review & editing, Writing – original draft, Supervision, Methodology, Formal analysis, Data curation,

Conceptualization. **Haïzam Oubari:** Writing – review & editing. **Louise Callens:** Writing – review & editing. **Yanis Berkane:** Writing – review & editing. **Tom Quisenaerts:** Writing – review & editing. **François Saget:** Methodology, Formal analysis, Data curation. **Wiebren Tjalma:** Writing – review & editing. **Gunther Steenackers:** Writing – review & editing. **Curtis L. Cetrulo Jr:** Writing – review & editing. **Alexandre G. Lellouch:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Formal analysis, Data curation, Conceptualization. **Filip Thiessen Ef:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:Haizam Oubari, Yanis Berkane reports financial support was provided by Gueules Cassées Foundation, Société française de Chirurgie Plastique, Shriners Hospitals for Children. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

None.

References

[1] F.E.F. Thiessen, et al., Dynamic Infrared Thermography (DIRT) in DIEP flap breast reconstruction: a clinical study with a standardized measurement setup, Eur. J. Obstet. Gynecol. Reprod. Biol. 252 (2020) 166–173, https://doi.org/10.1016/j.ejogrb.2020.05.038 (in eng).
[2] N. Pereira, D. Valenzuela, G. Mangelsdorff, M. Kufeke, R. Roa, Detection of perforators for free flap planning using smartphone thermal imaging: a Concordance study with computed tomographic angiography in 120 perforators (in English), Plast. Reconstr. Surg. 141 (3) (2018) 787–792, https://doi.org/10.1097/prs.0000000000004126. Article.
[3] S.P. Nischwitz, et al., Thermal, Hyperspectral, and Laser Doppler imaging: non-invasive tools for detection of the deep inferior epigastric artery perforators-A Prospective Comparison study (in English), J. Personalized Med. 11 (10) (2021) 13, https://doi.org/10.3390/jpm11101005. Art no. 1005.
[4] S.S. Patel, C. Homsy, E.K. Atamian, A.E. Chaffin, Thermal imaging Facilitates design of a keystone perforator island flap for a myxofibrosarcoma resection reconstruction: case report, Plast Reconstr Surg Glob Open 7 (8) (2019) e2359, https://doi.org/10.1097/gox.0000000000002359 (in eng).
[5] S.P. Paul, Using a thermal imaging camera to locate perforators on the lower limb, Arch Plast Surg 44 (3) (2017) 243–247, https://doi.org/10.5999/aps.2017.44.3.243 (in eng).
[6] S. Suphachokauychai, K. Kiranantawat, K. Sananpanich, Detection of perforators using smartphone thermal imaging, in: eng (Ed.), Plast Reconstr Surg Glob Open 4 (5) (2016) e722, https://doi.org/10.1097/gox.0000000000000715.
[7] O. Hennessy, R. McLoughlin, N. McInerney, A. Hussey, S. Potter, Smartphone thermal imaging for preoperative perforator mapping in DIEP flap breast reconstruction, Eur. J. Plast. Surg. 43 (2020) 1–8, https://doi.org/10.1007/s00238-020-01687-z.
[8] R. Chen, Z.Q. Huang, W.L. Chen, Z.P. Ou, S.H. Li, J.G. Wang, Value of a smartphone-compatible thermal imaging camera in the detection of peroneal artery perforators: comparative study with computed tomography angiography, Head Neck-J. Sci. Spec. Head Neck 41 (5) (2019) 1450–1456, https://doi.org/10.1002/hed.25581 (in English).
[9] G.G. Hallock, Smartphone thermal imaging can enable the safer use of propeller flaps, Semin. Plast. Surg. 34 (3) (2020) 161–164, https://doi.org/10.1055/s-0040-1714291 (in English).
[10] C. Illg, S. Krauss, J. Rothenberger, J. Kolbenschlag, A. Daigeler, R.C. Schafer, Air flow cooling improves anterolateral thigh perforator mapping using the FLIR ONE thermal camera, J. Reconstr. Microsurg. 38 (2) (2022) 144–150, https://doi.org/10.1055/s-0041-1731641 (in English).
[11] J.T. Hardwicke, O. Osmani, J.M. Skillman, Detection of perforators using smartphone thermal imaging, in: eng (Ed.), Plast. Reconstr. Surg. 137 (1) (2016) 39–41, https://doi.org/10.1097/prs.0000000000001849.
[12] W. Konczalik, D. Nikkhah, A. Mosahebi, Applications of Smartphone thermal camera imaging system in monitoring of the deep inferior epigastric perforator flap for breast reconstruction, Microsurgery 37 (5) (2017) 457–458, https://doi.org/10.1002/micr.30075 (in eng).
[13] W.S. Ko, T. Chiu, Detection of perforators using smartphone thermal imaging, Plast. Reconstr. Surg., Letter 138 (2) (2016) 380E–381E, https://doi.org/10.1097/prs.0000000000002361 (in English).
[14] N. Pereira, G.G. Hallock, Smartphone thermography for lower extremity local flap perforator mapping (in English), J. Reconstr. Microsurg. 37 (1) (2021) 59–66, https://doi.org/10.1055/s-0039-3402032. Article.
[15] G.G. Hallock, Dynamic infrared thermography and smartphone thermal imaging as an adjunct for preoperative, intraoperative, and postoperative perforator free flap monitoring, Plastic and Aesthetic Research 6 (2019) 29, https://doi.org/10.20517/2347-9264.2019.029.
[16] J.T. Hardwicke, J.M. Skillman, Reply: detection of perforators using smartphone thermal imaging, Plast. Reconstr. Surg., Letter 138 (5) (2016) 940E, https://doi.org/10.1097/prs.0000000000002719 (in English).
[17] S. Weum, A. Lott, L. de Weerd, Detection of perforators using smartphone thermal imaging, Plast. Reconstr. Surg. 138 (5) (Nov 2016) 938e–940e, https://doi.org/10.1097/prs.0000000000002718 (in eng).
[18] R. Sonda, et al., Deep inferior epigastric perforator flap preoperative planning: a comparative analysis between dynamic infrared thermography, computerized tomography angiography, and hand-held Doppler, Microsurgery 42 (7) (2022) 649–658, https://doi.org/10.1002/micr.30927 (in eng).
[19] M. Renzulli, et al., Preoperative computed tomography assessment for a deep inferior epigastric perforator (DIEP) flap: a new easy technique from the Bologna experience, Acta Radiol 62 (10) (2021) 1283–1289, https://doi.org/10.1177/0284185120963899 (in eng).
[20] T. Han, et al., A comparison of handheld Doppler and indocyanine green angiography for perforator localization, Ann. Plast. Surg. 89 (1) (2022) 89–94, https://doi.org/10.1097/sap.0000000000003203 (in eng).
[21] M.V. Muntean, P.A. Achimas-Cadariu, Detection of perforators for free flap planning using smartphone thermal imaging: a concordance study with computed tomographic angiography in 120 perforators, Plast. Reconstr. Surg., Letter 142 (4) (2018) 604E, https://doi.org/10.1097/prs.0000000000004751 (in English).