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Meta-Analysis

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Comparing microsurgical breast reconstruction outcomes following postoperative monitoring techniques: a systematic review and meta-analysis of 2529 patients

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Abstract

Aims: This paper aims to assess the existing evidence regarding oximetry and thermography by comparing postoperative rates of complications following microsurgical breast reconstruction.

Methods: A systematic review of PubMed, Web of Science, and Cochrane was completed. A qualitative and quantitative analysis of all included studies was then performed.

Results: Fourteen studies were included with a total population of 2,529 female patients who underwent microvascular breast reconstruction, ultimately totaling 3,289 flaps. The mean age for the cohorts included in this study ranged from 48.9 to 57 years of age. A total of 15 complete flap losses were reported. Furthermore, this meta-analysis of proportion showed that total flap loss experienced was 0% (95%CI 0%-100%) for patients monitored with thermography compared to 0% (95%CI 0%-1%) for those monitored with oximetry. Partial flap loss occurred at a frequency of 1% [95% confidence interval (CI) 0%-73%] for patients monitored with thermography compared to 1% (95%CI 0%-2%) for those monitored with oximetry. Furthermore, the results of this study showed that thermography prompted a return to the operating room (OR) in 1% (95%CI 0%-73%) of the patients compared to 5% (95%CI 3%-9%) for oximetry. Lastly, the overall complication rate was 12% (95%CI 1%-54%) for patients monitored with thermography compared to 10% (95%CI 4%-21%) for those monitored with oximetry.

Conclusion: Ultimately, this meta-analysis concludes that while oximetry monitoring currently has strong evidence for improving flap outcomes, trends in the current data indicate that further studies may demonstrate that thermography may be comparable to oximetry in achieving similar patient outcomes.

Keywords: Microsurgical breast reconstruction, oximetry, thermography, flap monitoring, flap take back, flap outcomes

INTRODUCTION

Flap failure is a devastating complication after microvascular free tissue transfer for breast reconstruction. Despite advancements in microvascular techniques, rates of take-backs to the operating room for complications leading to flap compromise have been reported at around 0%-10% for microsurgical breast reconstruction[1-10]. Historically, surgeons have relied on physical examination to assess flap viability by assessing color, warmth, capillary refill, and turgor[11]. Physical examination is also often used in conjunction with a handheld Doppler ultrasound[11]. Evidence has shown that early detection of vascular compromise in a threatened flap is essential for increasing rates of flap survival[1-8]. Given the need for timely diagnosis, several noninvasive methods of flap monitoring have emerged as useful adjuncts to conventional methods of evaluation of flap compromise.

In the past, authors described the ideal characteristics of a monitoring technique that is benign to both the patient and the free flap[12]. They determined that the ideal monitoring method would be rapid, repeatable, reliable, recordable, rapidly responsive, accurate, inexpensive, objective, and applicable to all kinds of flaps[12]. They also felt it should be equipped with a simple display that could alert relatively inexperienced personnel to the development of circulatory impairment[12]. Despite this thorough postulation of an ideal system, there is no standard of care for flap monitoring devices and no high-impact evidence that favors one technique over another.

Two technologies commonly mentioned in the literature for flap monitoring post-microsurgical breast reconstruction are oximetry and thermography. One available device utilizing oximetric monitoring is the ViOptix T.Ox Tissue Oximeter (ViOptix, Inc., Fremont, Calif.); this device is a noninvasive monitor of real-time flap perfusion that uses the emission of near-infrared light to measure local tissue oxygen saturation[13,14]. This technology has been shown to provide an increase in flap salvage rate and early detection of flap compromise. Another monitoring method is thermal imaging or dynamic infrared thermography (DIRT)[14]. Thermal imaging detects infrared radiation from an object and produces an image based on the local temperature, which can be used as a surrogate marker for cutaneous blood flow. Several studies have shown thermography's efficacy in preoperative planning to identify perforating vessels, but until more recently, technological impediments limited its use[14]. Handheld thermal imaging devices are now commercially available (FLIRONE, Flir Systems, Inc., Wilsonville, OR) and are becoming more affordable[14]. Further, they can be paired with most smartphones, making this technique very appealing for convenient postoperative monitoring[14]. However, despite its high potential, no studies have shown DIRT technology to be superior or comparable to other flap monitoring methods. The purpose of this systematic review was to clarify the existing evidence regarding oximetry and thermography by comparing postoperative rates of complications following microsurgical breast reconstruction.

METHODS

This study protocol was prospectively registered with PROSPERO (Study # ID: CRD42022360392)[15]. This systematic review followed the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) statement guidelines[15].

Eligibility criteria

Criteria for included studies were defined as adult female patients who underwent autologous breast reconstruction and were monitored with either oximetry or thermography. The full eligibility criteria are accessible at PROSPERO and are as follows:

Inclusion criteria:

· Adult female patients
· Patients who underwent autologous breast reconstruction (microvascular)
· Patients who were monitored with oximetry or thermography
· Observational studies and clinical trials
· Case Series and Case Reports with greater than 15 patients
· Studies in English, French, and Spanish

Exclusion criteria:

· Editorials;
· Commentary reports;
· Case series/Case Report with < 15 patients
· Abstracts with no full text available
· Letters to the editors; · Animal studies
· Cadaveric Studies
· Studies where breast flap-related outcomes could not be identified

Search strategy

A comprehensive research review using subject headings, controlled vocabulary, and keywords was conducted on 25 September, 2022, on MEDLINE (in Ovid), Web of Science, and the Cochrane Central Register for studies published until 2021. Our full-text search strategy is accessible at PROSPERO.

Study selection

The search results were uploaded into the online systematic review program Covidence to conduct study selection[16]. Six independent reviewers performed a two-screening process for study selection. (Hernandez Alvarez A, Valentine L, Weidman A, Devi K and Foppian JA). First, titles and abstracts were screened. A third reviewer (Foppian JA) moderated and if discordances were present, resolved the conflict. Next, a full-text analysis was performed by four of the reviewers (Foppian JA, Hernandez Alvarez A, Valentine L and Weidman A). If conflicts arose between reviewers, the third reviewer moderated a discussion to come to a joint decision.

Data extraction/synthesis

Data extraction was guided by a predetermined checklist: first author's last name, year of publication, total sample size, gender, type of flaps, the device used for monitoring, monitoring protocol, identification of threatened flaps, flap take back, rates of flap salvage, flap loss, complication including but not limited to: congestion, ischemia, infection, necrosis, and hematoma, etiology of complication and treatment of complication, time to identification of complications, and intervention for treatment of the complications.

Outcomes

The primary outcomes were detection of complications, identification of threatened flaps, patient return to the operating room (flap "take-back"), flap salvage, flap loss, and time to identification of complications.

Quality assessment

To assess the risk of bias, we utilized the National Institute of Health (NIH) quality assessment tool. Each article was categorized as follows: "low risk," "moderate risk," or "high risk" of bias.

Statistical analysis

A comprehensive qualitative analysis was made. For the quantitative analysis, the binomial data was analyzed. Each complication rate's pooled prevalence was estimated using a proportion meta-analysis with Stata statistical software (STATA Corp., College Station, TX version 16.1)[17]. Due to the heterogeneity among studies, a logistic-normal-random-effect model was conducted. Ninety-five percent exact confidence interval (CIs) and 95% Walds CIs were performed for study-specific and overall pooled prevalence, respectively. Additionally, the Freeman-Tukey double arcsine transformation was used. The percentage of weight and effect size of each individual study were presented[17,18]. To assess heterogeny, I^2 statistics were used. Significant heterogeneity was considered if pp-value < 0.05 or $I^2 > 50\%$.

RESULTS

Study selection and characteristics

A total of 614 studies were initially retrieved following the removal of duplicates. Of those, 18 met all inclusion criteria. However, 4 of the 18 articles contained duplicate or already published patient information and were removed. Therefore, 14 articles were ultimately included for qualitative and quantitative analysis [Figure 1][19-32]. Of the 14 articles, 11 were focused on oximetry, and 3 were focused on thermography. When using the NIH quality assessment tool, 7 were found to be at low risk of bias, 6 at moderate risk, and 1 at high risk based on the NIH quality assessment tool [Table 1][19-32]. The Prisma Flow diagram is seen in Figure 1.

Patient and flap characteristics [Table 1]

From all 14 included studies, a total of 2,529 female patients who underwent microvascular breast reconstruction were included in this analysis, which ultimately totaled 3,289 flaps overall[19-32]. The mean age for the cohorts included in this study ranged from 48.9 to 57 years of age. The most common flap used in the patient population was the deep inferior epigastric (DIEP) flap with 2,372 total flaps, followed by 96 transverse rectus abdominis (TRAM) flaps, 43 superior gluteal artery perforator (SGAP) flaps, 17 superficial inferior epigastric artery (SIEA) flaps, 8 profunda artery perforator (PAP), 6 diagonal/transverse upper gracilis (DUG/TUG) and 1 latissimus dorsi (LD) flap. The remainder of the flaps included 746 flaps described only as "abdominal-based flaps" and stacked flaps, which can be seen in Table 1[19-32].

Diagnostic tools and monitoring protocols

The studies included in this review used a variety of diagnostic tools for thermography and oximetry, each with its own nuances in terms of application and protocols.

In the realm of thermography, the study by Saxena *et al.* employed the FLIR A320 IR thermal camera, a specialized device designed for thermal imaging, while the research conducted by Phillips *et al.* utilized the FLIR One device, which is connected to a mobile smartphone for ease of use[20,21]. On the other hand, the study by Thiessen *et al.* did not explicitly indicate which tool was employed for dynamic infrared thermography[19]. Notably, the approaches to measurement in these studies showed some variation. Both Thiessen *et al.* and Saxena *et al.* conducted two measurements within the initial 1-2 days post-procedure,

Table 1. Study characteristics and flap demographics

Author	Type of study	NIH quality assessment	Number of participants	Mean age	Number of flaps	Type of flap
Thiessen *et al.*[19] 2020	Prospective observational	Moderate	21	56.7	33	1 TRAM 32 DIEP
Saxena *et al.*[20] 2019	Prospective observational	Moderate	32	51.9	32	32 TRAM
Phillips *et al.*[21] 2020	Prospective observational	Low	19	54.6	30	30 DIEP
Lindelauf *et al.*[22] 2021	Prospective observational	Moderate	30	51	42	42 DIEP
Johnson *et al.*[23] 2021	Retrospective observational	Low	460	50.7	740	740 "abdominal-based flaps"
Pelletier *et al.*[24] 2011	Randomized control	Low	50	49.2	50	14 TRAM 21 DIEP 9 SIEA 3 DIEP/SIEA double stacked flaps 3 DIEP/SIEV turbocharged flaps 1 DIEP + DIEP double stacked flap
Ricci *et al.*[25] 2017	Retrospective observational	Low	900	50.3	900	3 TRAM 872 DIEP 2 SIEA 23 SGAP
Ozturk *et al.*[26] 2014	Prospective observational	Moderate	20	49.3	30	4 TRAM 24 DIEP 2 SIEA
Saad *et al.*[27] 2020	Retrospective observational	Moderate	120	53	120	35 TRAM 85 DIEP
Salgarello *et al.*[28] 2018	Retrospective observational	Moderate	45	52.6	45	45 DIEP
Carruthers *et al.*[29] 2019	Retrospective observational	Low	196	50.7	301	301 DIEP
Tran *et al.*[30] 2021	Retrospective observational	Low	175	50.9	286	3 MS-TRAM 266 DIEP 3 SIEA 6 TUG/DUG 8 PAP
Kumbasar *et al.*[31] 2021	Prospective observational	High	10	57	10	1 TRAM 8 DIEP 1 LD
Koolen *et al.*[32] 2016	Retrospective observational	Low	451	48.9	670	3 TRAM 646 DIEP 1 SIEA 20 SGAP

NIH: National Institute of Health; DIEP: deep inferior epigastric; TRAM: transverse rectus abdominis; SGAP: superior gluteal artery perforator; SIEA: superficial inferior epigastric artery; PAP: profunda artery perforator; DUG/TUG: diagonal/transverse upper gracilis; LD: latissimus dorsi.

providing a short-term perspective on thermal changes[19,20]. Conversely, the study by Phillips *et al.* did not furnish details on their protocol for measurements, leaving some ambiguity in their approach[21].

Regarding oximetry, several studies-including those by Pelletier *et al.*, Ricci *et al.*, Ozturk *et al.*, Carruthers *et al.*, Tran *et al.*, Koolen *et al.*, and Johnson *et al.*-relied on the ViOptix tissue oximetry technology to monitor oxygen levels in tissue[23-26,29,30,32]. In contrast, Lindelauf *et al.* employed the Foresight MC-2030 oximeter, Saad *et al.* used the T-Stat tissue oximeter by Spectros, Salgarello *et al.* utilized the Somanetics INVOS 5,100 C Cerebral/Somatic Oximeter (Covidien), and Kumbasar opted for the INVOS 700 cerebral oximetry monitoring system[22,27,28,31]. The protocols for the use of these diagnostic tools exhibited some

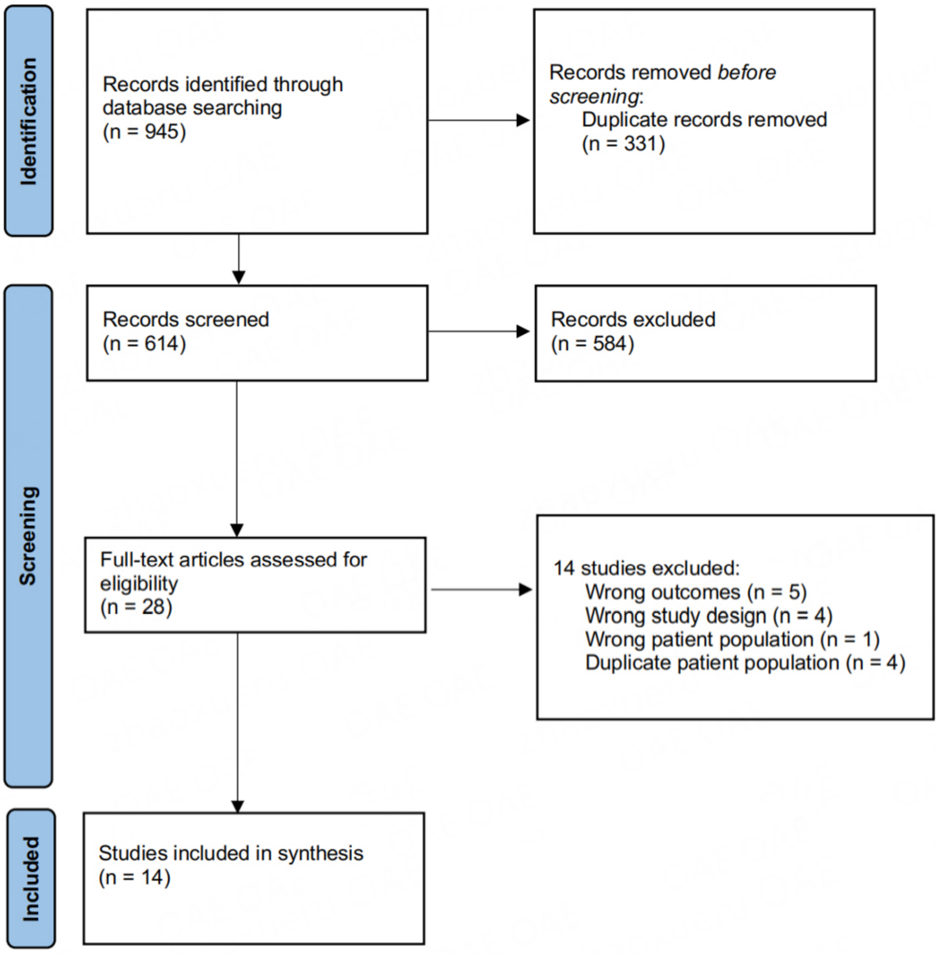

Figure 1. Systematic Reviews and Meta-analysis (PRISMA) guidelines flow diagram.

variance among the studies. Salgaretto *et al.*, Kumbasar *et al.*, and Koolen *et al.* recorded measurements continuously for a minimum of two days after the conclusion of the procedure, providing a continuous record of tissue oxygenation[28,31,32]. The remaining studies, meanwhile, opted for interval readings, though the specific timing of these readings differed slightly between studies [Table 2].

Meta-analysis of complications [Table 3]

The pooled prevalence of complication-related outcomes was calculated through a meta-analysis random effects model of proportion. The pooled prevalence of flaps determined to be threatened was 0.05 (95%CI 0.03-0.10) for studies using oximetry and 0.10 (95%CI 0.02-0.11) for those using thermography [Supplementary Digital 1]. In studies using oximetry, the pooled prevalence of partial flap loss was 0.01 (95%CI 0.00-0.02) and 0.00 (95%CI 0.00-0.01) for complete flap loss. In those using thermography, the pooled prevalence of partial flap loss was also 0.01 (95%CI 0.00-0.73) and 0.00 (95%CI 0.00-1.00) for complete loss. With regards to the rate of flap salvage, the pooled prevalence of salvage in studies using oximetry was 0.06 (95%CI 0.03-0.11) compared to 0.23 (95%CI 0.14-0.35) in those using thermography, indicating that thermography was superior in facilitating salvage to compromised flaps [Supplementary Digital 2]. The pooled prevalence of the rate of return to the operating room was 0.05 (95%CI 0.03-0.09) for studies using oximetry and 0.01 (95% CI 0.00-0.73) for thermography [Supplementary Digital 3]. Further, in studies using postoperative oximetry, the pooled prevalence rates of the remaining flap complications

Table 2. Monitoring protocols in thermography and oximetry groups

Lead author and publication date	Diagnostic method	Diagnostic tool	Time frame of use	Protocol for diagnostic tool	Cut-off values used for concern	Length of monitoring period
Thiessen *et al*[19]. 2020	Thermography	Unspecified	Preoperative, intraoperative and postoperative	Once preoperative to determine perforators. Intraoperatively, first after perforator dissection to confirm patency, then a second after the microvascular anastomosis, then a third after flap inset Postoperatively, 2 measurements taken 1-2 days following surgery	N/a	24-48 h
Saxena *et al*.[20] 2019	Thermography	FLIR A320 IR thermal camera	Postoperative	Measurement immediately after the procedure and one day (24 h) after the procedure	N/a	24 h
Phillips *et al*.[21] 2020	Thermography	FLIR one device connected to an iPhone 7 smartphone	Intraoperative, postoperative	Intraoperatively after isolation on its vascular pedicle, at max ischemia before anastomosis, in 5-minute intervals after completion of microvascular anastomosis, and before leaving the OR Postoperatively, used whenever there was concern for flap viability	N/a	N/a
Lindelauf *et al*.[22] 2021	Oximetry	Foresight MC-2030 oximeter	Preoperative and postoperative	Preoperative baseline measurements were performed. A new sensor was positioned postoperatively on the transplanted tissue. In unilateral procedures, postoperative StO2 values of the native breast were also obtained. Measurements were continued for 24 h	N/a	24 h
Johnson *et al*.[23] 2021	Oximetry	ViOptix	Intraoperative and postoperative	Intraoperatively following anastomosis. Postoperatively, hourly checks by nursing staff until the second postoperative morning, followed by every other hour monitoring for the second to third postoperative days, and every fourth-hour monitoring from the third postoperative morning through discharge	Any change 10% or greater	Though discharge with a mean of 4.8 days
Pelletier *et al*.[24] 2011	Oximetry	ViOptix	Postoperative	Measurements every 4-6 h until discharge	An StO2 level below 30% or a drop in StO2 level of > 20% per hour lasting for 30 minutes	Until discharge with a mean of 3.1 days (ICU group) and 2.7 days (floor group)
Ricci *et al*.[25] 2017	Oximetry	ViOptix	Postoperative	Monitored continuously with tissue oximetry for three consecutive days, beginning immediately following the procedure	A rapid 20-point drop from baseline in 1 h or an absolute recording < 30 percent	72 h
Ozturk *et al*.[26] 2014	Oximetry	ViOptix	Intraoperative and postoperative	Readings were recorded prior to extubation, after extubation and every 4 h for the next 36 h	N/a	36 h
Saad *et al*.[27] 2020	Oximetry	T-Stat tissue oximeter by Spectros	Postoperative	Tissue oximetry readings were recorded immediately at the completion of the reconstruction at hours 1, 2, 3, 4, 6, 12, and 24	N/a	24 h
Salgarello *et al*.[28] 2018	Oximetry	Somanetics INVOS 5100C Cerebral/Somatic Oximeter (Covidien)	Postoperative	Measurements recorded continuously for 48 h starting in the post-anesthesia care unit	An rSO2 value of 30% or drop rate in rSO2 by 20%	48 h
Carruthers *et al*.[29] 2019	Oximetry	ViOptix	Intraoperative and postoperative	Probe applied intraoperatively to skin paddle and remained on until discharge, measurements recorded continuously	N/a	Until discharge with a mean of 3.4 days

Tran *et al.*[30] 2021	Oximetry	ViOptix	Intraoperative and postoperative	Probe placed on skin island intraoperatively after flap inset, remained and took continuous readings during the hospitalization	A decrease in tissue saturation readings of 20 points from the postoperative baseline	Until discharge (no mean length of stay provided)
Kumbasar *et al.*[31] 2021	Oximetry	INVOS 700 cerebral oximetry monitoring system	Postoperative	Continuous monitoring began postoperatively in the post-anesthesia care unit and remained until discharge	A 10% decrease in oximetry levels, critical tissue oximetry measurements as a skeletal muscle oxygen saturation level below 65%, or a drop in StO2 level of more than 20% lasting for 20 minutes	72 h
Koolen *et al.*[32] 2016	Oximetry	ViOptix	Postoperative	Probe was placed onto the surface of the flap in the operating room at the conclusion of the procedure and left in place for 3 days	A rapid 20-point drop from baseline in 1 h or an absolute recording less than 30 percent	72 h

OR: operating room.

assessed were: 0.02 (95%CI 0.01-0.03) for congestion, 0.03 (95%CI 0.01-0.13) for necrosis, 0.03 (95%CI 0.02-0.03) for hematoma and 0.01 (95%CI 0.00-0.16) for infection. In studies using postoperative thermography, the pooled prevalence rates of the remaining flap complications assessed were: 0.03 (95%CI 0.00-0.29) for congestion, 0.04 (95%CI 0.00-0.36) for necrosis, 0.00 (95%CI 0.00-1.00) for hematoma and 0.04 (95%CI 0.00-0.56) for infection. The overall pooled prevalence of complications in studies using oximetry was 0.10 (95%CI 0.04-0.21) compared to 0.12 (95%CI 0.01-0.54) for those using thermography [Supplementary Digital 4]. Additional forest plots demonstrating the results of this meta-analysis are available in the supplemental materials section [Supplementary Digitals 5-10] [Table 3].

DISCUSSION

This meta-analysis is the first study to extensively investigate the current state of literature comparing the use of thermography to oximetry following microsurgical breast reconstruction for flap monitoring. Oximetry has been described thoroughly in the literature and has significantly contributed to breast reconstruction outcomes by identifying threatened flaps before or in conjunction with physical examination findings[14]. Thermography for flap monitoring has also been documented, but until more recently, technological impediments limited its use[14]. In recent years, advances in smartphones and portable cameras have driven its resurgence[14,21]. However, a question remains regarding the usefulness of thermography compared to oximetry. The results of this systematic review show that limited high-level evidence exists regarding thermography as opposed to oximetry. The evidence that is available regarding each method indicates that the two modalities may have comparable outcomes. Therefore, additional investigation could show the utility of thermography as an adjunct or alternative to oximetry. Ultimately, evidence for the use of oximetry due to better salvage rate and lower overall complication rates may be stronger than that for thermography. However, both modalities have the potential to improve outcomes, especially given additional research and development.

This meta-analysis showed that partial flap loss occurred at a frequency of 1% for patients monitored with thermography compared to 1% for those monitored with oximetry. Total flap loss was experienced by 0% for patients monitored with thermography compared to 0% for those monitored with oximetry. These results demonstrated that thermography has similar results to oximetry regarding partial and total flap loss. This emphasizes that both types of monitoring

Table 3. Outcomes of thermography *vs.* oximetry monitoring

>Complication rates	Number of studies	Total	Prevalence [95%CI]	I^2 (%)
		Threatened flaps		
Overall	14	206/3,289	0.06 [0.03, 0.11]	91%
Thermography	3	14/95	0.10 [0.02, 0.42]	0%
Oximetry	11	192/3,194	0.05 [0.03, 0.10]	92%
		Partial flap loss		
Overall	14	37/3,289	0.01 [0.00; 0.03]	28%
Thermography	3	9/95	0.01 [0.00, 0.73]	0%
Oximetry	11	28/3,194	0.01 [0.00, 0.02]	100%
		Complete flap loss		
Overall	14	15/3,289	0.00 [0.00; 0.01]	0%
Thermography	3	0/95	0.00 [0.00, 1.00]	0%
Oximetry	11	15/3,194	0.00 [0.00, 0.01]	0%
		Necrosis		
Overall	8	158/1,802	0.03 [0.01, 0.12]	77%
Thermography	3	10/95	0.04 [0.00, 0.36]	60%
Oximetry	5	148/1,707	0.03 [0.01, 0.13]	78%
		Congestion		
Overall	8	37/1,527	0.02 [0.01, 0.04]	38%
Thermography	2	3/63	0.03 [0.00, 0.29]	0%
Oximetry	6	34/1,464	0.02 [0.01, 0.04]	25%
		Hematoma		
Overall	9	62/2,427	0.03 [0.02, 0.03]	0%
Thermography	2	0/63	0.00 [0.00, 1.00]	0%
Oximetry	7	62/2,364	0.03 [0.02, 0.03]	0%
		Infection		
Overall	6	67/1,803	0.01 [0.00, 0.13]	1%
Thermography	2	5/63	0.04 [0.00, 0.56]	0%
Oximetry	4	62/1,740	0.01 [0.00, 0.16]	0%
		Return to OR		
Overall	10	179/2,504	0.05 [0.02, 0.09]	87%
Thermography	2	9/95	0.01 [0.00, 0.73]	0%
Oximetry	8	170/2,409	0.05 [0.03, 0.09]	87%
		Rate of salvage		
Overall	10	190/3,171	0.06 [0.03, 0.11]	94%
Thermography	2	14/62	0.23 [0.14, 0.35]	12%
Oximetry	8	176/3,109	0.12 [0.05, 0.33]	94%

OR: operating room.

may have their roles as efficacious monitoring tools to identify and prompt successful interventions in breast microvascular reconstruction. Compared to the existing literature, both sub-groups of studies included in this meta-analysis show better outcomes for partial and complete flap loss rates. Indeed, the literature reports partial flap loss in up to 9% of patients undergoing autologous breast reconstruction and complete flap loss in less than 5% of patients[1-10,33,34]. If not for the postoperative monitoring in each of our studies, it could be hypothesized that a larger proportion of patients who had partial flap failure would have progressed to total flap failure instead. Noninvasive, postoperative monitoring of breast flaps provides plastic surgeons a chance to identify threatened flaps before they show physical signs of distress and require additional therapy. As a result, flaps that may have otherwise been lost can be completely salvaged or only partially lost instead.

In the pooled patient population, skin necrosis was present in 4% of the patients monitored with thermography compared to 3% for those monitored with oximetry. Based on our results, oximetry seems to be marginally better suited for preventing this type of complication. A study by Olsen *et al.* showed a cumulative 14% complication rate for non-infectious surgical site complications in 1,799 of their patients who underwent autologous breast reconstruction[35]. This rate is higher than in either of the sub-groups presented in this study and demonstrates the potential benefits that both oximetry and thermography as postoperative monitoring tools may bring to patients undergoing autologous breast reconstruction. It is also important to note that Olsen *et al.* acknowledged a high possibility of under-reporting this type of complication within their cohort, further strengthening the evidence supporting the implementation of either of the monitoring tools presented in our paper[35].

Additionally, this meta-analysis showed that the overall complication rate for flaps used in autologous breast reconstruction was 12% for patients monitored with thermography compared to 10% for those monitored with oximetry. Bennet *et al.*, in a study with a multicenter cohort of 706 patients who underwent autologous breast reconstruction, showed an overall complication rate of 46.7% with a re-operation rate of 27.6%[36]. On the other hand, Mehrara *et al.* showed an overall complication rate of 27.95% in 952 patients who underwent microvascular breast reconstruction[1]. Therefore, the results of this meta-analysis may show better outcomes in terms of overall complications than reported in the literature.

Furthermore, the results of this study showed that thermography prompted a return to the OR in 1% of the patients compared to 5% for oximetry. A study by Shammas *et al.* previously showed an overall return to the OR of 11% and, notably, a 27.8% return to the OR for their sub-patient population who underwent staged autologous procedures as compared to immediate microsurgical reconstruction[33]. It is interesting to note that while the take-back rate in our included studies was lower than in some of the literature, the outcomes were better than in most of the literature. While no causality can be determined, the monitoring could be hypothesized to have objectively and accurately identified flaps that required true intervention, leading to fewer take-backs but also more meaningful take-backs.

While there were no unified postoperative monitoring protocols across the studies, a trend was present. There was often an emphasis on either continuous or more frequent monitoring during the first 24 h postoperatively. This trend can be explained by Carruthers, 2019, who describe in their studies that nearly 96% of major complications of microsurgical breast reconstruction occur within those first 24 h following surgery[29]. These findings highlight the justifiable importance of more rigorous monitoring during this postoperative timeframe. Thus, while studies, such as that by Moderhak *et al.*, reported monitoring for up to 3 months in their cohort postoperatively, the focus of oximetry, thermography, or any postoperative monitoring method should prioritize this critical 24-hour time period regardless of surgeons' skills or center capabilities[37].

Of note, Phillips *et al.* described 19 patients who underwent 30 DIEAP flaps for breast reconstruction and monitored their patients using mobile smartphone thermography, demonstrating good outcomes[21]. Advances such as this are crucial to take into account, as cost efficiency is critical to medical practice. While some re-usable thermographic cameras can cost up to 20,000 USD, smartphone cameras are more affordable and can reduce the cost to as low as 200 USD[38]. Additionally, a study by Schoenbrunner *et al.* showed that oximetric monitoring raised the cost of postoperative flap monitoring by 2,000 USD per patient with devices costing 8,000-50,000 USD[39,40]. While this implies that the cost of both those types of monitoring is similar, the newer smartphone-based monitoring could become a compelling cost-efficient method. Continuing with the discussion of cost efficiency, another important factor to consider is the economic burden that results from flap complications and flap loss. Complications associated with autologous breast reconstruction are costly, with median costs for complications at 30 days found to be an additional $7,197 USD and at one year found to be an additional $10,644 USD[41]. Therefore, the price of monitoring flap perfusion may ultimately be more cost-effective for the sake of avoiding eventual flap complications and loss while certainly preventing additional psychological burden on patients.

Limitations

While this is an original and pioneering study that aims to systematically review and compare the outcomes and complications of oximetric and thermographic flap monitoring for microvascular flap monitoring, it does have limitations. Given the specific type of outcome investigated and the paucity of experimental designs in this domain, it was not feasible to restrict study designs to only randomized controlled trials or case-control cohorts, resulting in high heterogenicity. The final patient population was thus retrieved largely from observational studies, which present biases inherent to their design (e.g., underreporting or information bias, and publication bias) and frequently incomplete data. This is a natural outcome when venturing into new territory and collecting data from multiple sources. Despite this limitation, our study represents a crucial first step in understanding the utility of thermography and oximetry for flap monitoring in microvascular breast reconstruction. Future research can build on our findings by comparing these monitoring techniques in a larger, more standardized patient cohort, with careful consideration of patient characteristics and comorbidities to enhance the rigor and precision of the comparison. Another significant limitation was the lack of consensus on what defines certain complications. For example, flap and skin necrosis were not reported in terms of area or percentage. Thus, some studies could have considered small defects while others may have chosen to only count larger areas of necrosis as a reportable complication. Furthermore, while postoperative monitoring can significantly impact outcomes, surgical experience, the volume of free flap performed in each institution, and variation in surgical technique can all have a major impact on complication rates. Lastly, it is important to note that a consensus on a unified cut-off indicating concern for a threatened flap when using oximetry or thermography should be established. Such a consensus could decrease heterogeneity within sub-groups and enable a more valid comparison of methods of breast flap monitoring.

CONCLUSION

Ultimately, this meta-analysis concludes that while oximetry monitoring currently has strong evidence for improving flap outcomes trends, the current data indicate that further studies may show that more updated, modern thermography is at least comparable to oximetry in achieving ideal patient outcomes. As of this systematic review, oximetry seems to be marginally superior to thermography and thus poses whether it would be valuable to put more resources into investigating thermographic monitoring techniques for microsurgical breast reconstruction. However, while outcomes themselves would not warrant further investigation, the emergent low-cost thermographic devices have the potential to improve cost-efficiency. Finally, this study highlights the importance of flap monitoring following microsurgical reconstruction of the breast and also encourages further cost analysis comparing thermography and oximetry.

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Authors' contributions

Initiating and designing the study and drafting the protocol: Foppian JA, Hernandez Alvarez A, Weidman A, Valentine L

Involved in the study design, optimizing the literature search, and resolving conflicts for the paper's inclusion: Foppian JA, Hernandez Alvarez A, Weidman A, Stearns S, Valentine L

Overseeing all aspects of study design and SR writing: Lin SJ

Availability of data and materials

All relevant information for this systematic review is either part of the manuscript, figures, tables and digital supplemental content. Any additional information can be found on the PROSPERO protocol for this paper. If any further information is required or unclear, the reader is more than welcome to contact the corresponding author for clarification.

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