Diagnostical Accuracy of Hyperspectral Imaging After Free Flap Surgery

Torsten Schulz (✉ torsten.schulz1988@gmail.com)

University Hospital Leipzig

Rima Nuwayhid

University Hospital Leipzig

Khosrow Siamak Houschyar

Hautzentrum Köln

Stefan Langer

University Hospital Leipzig

Lukas Kohler

University Hospital Munich

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Abstract

Background: Microsurgical free-tissue transfer has been a safe option for tissue reconstruction in the last decades. Reliable perfusion assessments must be performed to increase the safety of the procedure and facilitate decision-making regarding postoperative reinterventions. Therefore, the present study analyzed the diagnostic accuracy of hyperspectral imaging (HSI) after free-tissue transfer surgery.

Methods: From January 2017 to October 2019, 42 consecutive free-flap surgeries were performed, and their outcomes were analyzed via HSI. Clinical examination of free-flap perfusion was initially performed. The clinical examination findings were subsequently compared with those of HSI. Next, decision-making and postoperative complications rates were analyzed. Potential venous congestion with subsequent necrosis was defined as a tissue hemoglobin index of $\geq 53\%$. To compare two sets of data a student's *t*-test was used. The sensitivity and specificity for detecting flap failure were evaluated based on the dependence of time using the Fisher's exact test. A *p*-value of ≤ 0.05 was considered statistically significant.

Results: The success rate of microsurgical tissue transfer was 83.2%. Seven patients presented with venous congestion, causing total flap necrosis. All flaps required additional surgery, debridement, and tissue reconstruction. 124 assessments were made. HSI accurately identified 11 out of 13 pathological images. Three images were identified as false positive and two images as false negative. The sensitivity and specificity of HSI were 84% and 97%, with the positive and negative predictive values of 78% and 98%, respectively.

Conclusions: A tissue hemoglobin index of $\geq 53\%$ could predict a venous congestion after free-flap surgery within the first 72 h post operation. HSI could reasonably correlate with clinical observation. Until now, HSI does not show any superiority over any other monitoring modality.

Background

Microsurgery has been a major part of reconstructive surgery, and the technique has improved significantly over the last decades. Complex tissue defect reconstruction via free-flap surgery is safe and reliable [1]. Owing to technical progress and microsurgical expertise, the success rate continually increased up to 95% [2]. Despite these advances, ischemia-related complications can still occur after pedicled or free-tissue transfer, resulting in partial or complete flap loss. Therefore, microsurgical management aims to continually reduce ischemia-related morbidity and facilitate safe reconstruction [3]. Although free-tissue transfer was developed through supramicrosurgery, lymphatic vessel surgery, or chimeric free-flap surgery, postoperative perfusion control remains simple.

In German-speaking countries, reconstructive clinics generally rely on the clinical assessment of visual perfusion control (i.e., recirculation time of 3 s within the first 72 h) [4]. Although different technical devices have been introduced, they have several requirements (e.g., wide availability, neutral cost and personal resources, easy data interpretation, independence from the surgical method, and reliability) [4]. Hyperspectral imaging (HSI) is an imaging technique that collects information from the electromagnetic spectrum ranging from 500 to 1000 nm. Thus, it can analyze tissue-specific perfusion in a single image. HSI was first used in human medicine approximately 10 years ago, and it has since been applied in several scientific areas [5, 6].

Up until now, five different studies have been published about the clinical use of HSI for flap monitoring in tissue reconstructive surgery [7]. Recent studies suggested a decreased oxygenation to indicate flap malperfusion. However, different thresholds were postulated [8, 9]. In head and neck surgery, thresholds regarding the superficial or deep tissue oxygenation were hypothesized to be the optimal parameters for operative revisions in different kinds of impaired flap perfusion (arterial occlusion or venous congestion). Other parameters like hemoglobin or water concentrations in the tissue were not mentioned [9]. Furthermore, distributions among the different kinds of malperfusion were not taken into account. The present study aimed to assess the perfusion of free flaps postoperatively, compare our internal analysis software algorithm with the clinical findings of surgeons, and describe the accuracy of HSI using a contingency table. We hypothesized that a tissue hemoglobin index (THI) of $\geq 53\%$ can accurately indicate venous congestion.

Methods

Patients

In this retrospective, non-randomized study, patients with free flaps for reconstruction of the trunk and the extremities were included. The study was carried out with the help of an internal HSI database. From January 2017 to October 2019, a total of 31 men and 9 women with a median age of 55 ± 15.7 (26–92) years were recorded. Only free flaps with an intact skin paddle were included. Buried flaps, flaps

without a monitor island, or flaps with partial skin necrosis were not taken into account. Further, invalid or missing datasets were excluded. Clinical and instrumental examinations were performed by physicians. Data regarding defect etiology, comorbidities, and flap recipient site were recorded.

The primary outcomes were divided into two: regular flap healing and postoperative flap necrosis. Microvascular free-flap raising was performed according to standard procedures. After microsurgical anastomoses, tissue perfusion was initially assessed through clinical examination (capillary blanching and refill, skin color, and dermal bleeding) in a standardized manner after 1 h. Thereafter, tissue perfusion was evaluated using HSI. Hypo- or malperfused flaps were marked after assessment and compared with clinical findings. Based on the temporal context of the measurements, the three groups were classified as follows: measurements ≤ 24 h (t1), measurements between 24 and 48 h (t2), and measurements between 48 and 72 h (t3). Arterial occlusion was defined as a sudden pale color, prolonged or absent capillary refill time, and no bleeding, whereas venous congestion was defined as a blue color, immediate capillary refill, deep red bleeding on puncture, and subsequent flap necrosis. For this purpose, a marker was placed over the central parts of the skin island using the manufacturer's software, and the corresponding values were noted. Data regarding clinical assessment and HSI findings were entered in our departmental database. Due to the retrospective nature of this study, the final decision to re-explore has always been made based on clinical evaluation.

HSI and technical details

Postoperative HSI was performed using TIVITA® Tissue (Fig. 1A–G) via Diaspective Vision GmbH (Strandstrasse 15, D- 182333 Am Salzhaff, Germany). The system comprises a lighting unit with two 120-W halogen lamps, an imaging spectrometer, and a complementary metal-oxide-semiconductor camera with a resolution of 640×480 megapixels for image recording. HSI can measure the tissue perfusion discontinuously and is noninvasive, recordable, and easy to use; a single measurement lasts for 5 s. The distance between the camera and tissue was set at 50 cm. A standardized area of 30×30 cm can be assessed using HSI. The reduction of light (e.g., sunlight and room lighting) is recommended for optimal data quality. The underlying principle of HSI is based on remission spectroscopic measurements in the visible and near-infrared spectrum ranging from 500 to 1000 nm. The target is illuminated, and the altered light reflected from the tissue is displayed. Hemoglobin is the predominant optical component of the tissues, and oxygenated hemoglobin and reduced hemoglobin varies between vital or ischemic tissues. A different tissue penetration depth of visible light (approximately 0.5 mm) and the near-infrared spectral range (3–5 mm) lead to inferences regarding the upper tissue layer (microcirculation) and blood flow parameters at a deeper depth [6]. The four parameters measured using the software were the hemoglobin oxygenation at the superficial skin (StO_2), hemoglobin concentration at the superficial level (THI), near-infrared spectroscopy (NIR), and the tissue water index (TWI) [6, 10]. A THI of $\geq 53\%$, NIR of $\leq 25\%$, and TWI of $\leq 43\%$ indicated a locally impaired perfusion and a THI of $\geq 53\%$ of the whole flap indicated venous congestion [11]. Images were assessed using TIVITA Suite® (Diaspective Vision, Germany). The study was conducted as per the Declaration of Helsinki (updated in 2008) and approved by the ethics committee of the Ärztekammer Sachsen-Anhalt, Germany (Approval 35-17).

The skin paddles of the free flaps were examined. First, the flap was inspected clinically for malperfusion signs. The area with normally perfused flap, if present, was marked for measurement. Venous congestion with subsequent necrosis was defined as a THI of $\geq 53\%$. After image acquisition, all four parameters of the marked areas were calculated using the software for analysis provided by manufacturer.

Statistical analysis

All statistical analyses were performed using Xlstat® (version 2020.3.1, Addinsoft, New York, the USA). Means with standard deviations or numbers with percentages were used for descriptive statistics. To compare two sets of data a student's *t*-test was used. To assess the diagnostic reliability of the postoperative clinical findings or HSI assessments, the sensitivity, specificity, and positive and negative predictive values were calculated and presented in a contingency table. A *p*-value of <0.05 was considered statistically significant.

Results

In fact, 42 free-flap surgeries were analyzed. Table 1 shows the characteristics of patients and clinical data. The free flaps included 25 anterolateral thigh (ALT), 10 latissimus dorsi muscle (LDM), 5 deep inferior epigastric perforator (DIEP) flaps as well as 1 parascapular (PSC) and 1 rectus abdominis flap. The causes of reconstruction included traumatic injuries ($n = 32$, 76.2%), wound infections ($n = 6$, 14.2%), oncologic defects ($n = 3$, 7.2%), and peripheral occlusive diseases ($n = 1$, 2.4%). The lower extremity was the most common recipient site ($n = 30$; 71.4%), followed by the upper extremity ($n = 8$; 19.0%), chest ($n = 2$; 4.8%), head ($n = 1$; 2.4%), and abdomen ($n = 1$; 2.4%). A total of 35 patients underwent successful reconstruction. Hence, the overall flap success rate was 83.2%. 16.8% of our reconstructive cases resulted in a flap failure. Each patient further required surgical intervention. The mean length of hospital stay was 34

± 26 (range: 12–124) days. The hyperspectral data sets of each patient were recorded based on the perfusion status and time. Malperfusion in the form of an arterial occlusion was not observed. Based on time, the flaps could be classified into three subgroups.

Table 1
Characteristic of patients, THI values, clinical- and HSI findings in regard to each point.

Characteristic of patients, THI values, clinical and HSI findings in regard to each point.														
					t1			t2			t3			Flap failure
					status: vital = 0, noticeable = 1			status: vital = 0, noticeable = 1			status: vital = 0, noticeable = 1			
nr.	Sex	Age (years)	Flap	Cause	Clinical status	HSI status	THI	Clinical status	HSI status	THI	Clinical status	HSI status	THI	
true positive														
20	F	55	Rectus	POVD	1	1	55	1	1	59	1	0	49	1
31	F	61	ALT	Trauma	1	1	93	0						1
41	M	54	ALT	Trauma	0	1	53	1	1	59	1	1	59	1
2	M	39	DIEP	Trauma	0	0	52	1	1	64	1	1	74	1
10	M	60	LDM	Infection	0	0	52	1	1	68	1	0	33	1
4	F	80	ALT	Infection	0	0	41	0	0	10	1	1	58	1
26	M	61	LDM	Trauma	0	0	3	0	0	3	1	1	66	1
false positive														
9	M	62	ALT	Trauma	0	1	74	0	0	8	0	0	25	0
33	M	62	ALT	Trauma	0	1	63	0	1	60	0	0	48	0
false negative														
10	M	60	LDM	Infection	0	0	52	1	1	68	1	0	33	1
20	F	55	Rectus	POVD	1	1	55	1	1	59	1	0	49	1
true negative														
1	M	92	ALT	Trauma	0	0	3	0	0	3	0	0	8	0
3	M	26	DIEP	Trauma	0	0	46	0	0	15	0	0	27	0
5	M	57	ALT	Trauma	0	0	19	0	0	21	0	0	21	0
6	M	60	ALT	Trauma	0	0	41	0	0	42	0	0	44	0
7	M	30	Para	Trauma	0	0	45	0	0	17	0	0	27	0
8	M	51	ALT	Trauma	0	0	34	0	0	45	0	0	18	0
11	M	68	ALT	Trauma	0	0	37	0	0	16	0	0	6	0
12	M	78	ALT	Infection	0	0	40	0	0	43	0	0	44	0
13	M	37	ALT	Infection	0	0	20	0	0	7	0	0	11	0
14	M	50	ALT	Trauma	0	0	4	0	0	4	0	0	2	0
15	F	53	DIEP	Cancer	0	0	1	0	0	10	0	0	11	0
16	F	37	DIEP	Cancer	0	0	2	0	0	5	0	0	15	0
17	M	51	LDM	Infection	0	0	20	0	0	14	0	0	22	0
18	M	67	ALT	Trauma	0	0	15	0	0	9	0	0	5	0
19	F	62	DIEP	Cancer	0	0	28	0	0	24	0	0	28	0
21	M	66	LDM	Trauma	0	0	8	0	0	13	0	0	27	0
22	M	47	LDM	Trauma	0	0	52	0	0	32	0	0	25	0

nr.	Sex	Age (years)	Flap	Cause	t1 status: vital = 0, noticeable = 1			t2 status: vital = 0, noticeable = 1			t3 status: vital = 0, noticeable = 1			Flap failure
					Clinical status	HSI status	THI	Clinical status	HSI status	THI	Clinical status	HSI status	THI	
23	M	77	LDM	Trauma	0	0	15	0	0	15	0	0	19	0
24	F	87	LDM	Tumor	0	0	16	0	0	16	0	0	24	0
25	M	67	LDM	Trauma	0	0	53	0	0	38	0	0	28	0
27	M	55	LDM	Trauma	0	0	52	0	0	46	0	0	45	0
28	F	66	LDM	Trauma	0	0	21	0	0	12	0	0	15	0
29	M	56	ALT	Trauma	0	0	11	0	0	23	0	0	27	0
30	M	61	ALT	Trauma	0	0	30	0	0	24	0	0	27	0
32	M	32	ALT	Trauma	0	0	30	0	0	19	0	0	14	0
34	M	58	ALT	Trauma	0	0	20	0	0	11	0	0	12	0
35	M	24	ALT	Infection	0	0	25	0	0	29	0	0	28	0
36	M	62	ALT	Trauma	0	0	36	0	0	20	0	0	21	0
37	M	60	ALT	Trauma	0	0	4	0	0	0	0	0	0	0
38	F	47	ALT	Trauma	0	0	4	0	0	0	0	0	1	0
39	M	24	ALT	Trauma	0	0	9	0	0	10	0	0	2	0
40	M	58	ALT	Trauma	0	0	14	0	0	16	0	0	11	0
42	M	56	ALT	Trauma	0	0	17	0	0	10	0	0	9	0

HSI data

The corresponding HSI data of each patient were recorded. In total, 124 records were prepared, and 111 measurements were made on the viable flap areas. Moreover, 13 datasets of free flaps with venous congestion were analyzed. The average StO₂ was 44.5% ± 15.2% [3–80]; NIR, 41.0% ± 11% [7–72], and a THI of 27.2% ± 20.1% [0–93] concerning viable flaps (Fig. 2A-C). Free flaps with impaired perfusion in form of venous congestion were characterized by a decreased StO₂ (35.5%) and NIR (26.3%) and an increased THI up to 64.3% after three days. Student's *t*-test was performed between the groups for each parameter. No significant differences were found in terms of StO₂ between viable free flaps and flaps with malperfusion caused by venous congestion at each time point. However, regarding the NIR and THI, statistically significant differences were demonstrated.

Subgroup t1: Within the first 24 h, case number 20 and 31 developed a malperfusion in form of a venous congestion in clinical- and instrumental assessments. Operative revision was required. Intraoperatively, the venous anastomoses were thrombosed in both cases. In case 31, the patient presented with multiple thrombosis after reanastomosis. Therefore, the flap was directly removed intraoperatively. Further measurements could not be performed. Cases 20 demonstrated a regular recapillarization after a successful revision. In regarding to case 41, the HSI camera indicated the beginning of venous congestion. The clinical situation was rated as unremarkable. However, the venous congestion was progressive with a further deterioration in the period t2 so that an operative revision was finally initiated, and the suspicion was confirmed intraoperatively in form of a thrombosed vein. The case was also rated as true positive (Fig. 3). All three cases (20, 31, and 41) were rated as true positive.

Cases 9 and 33 had clinical viable flaps. However, there was a discrepancy between clinical findings indicating overall good flap perfusion and HSI suggesting venous congestion. Postoperative healing was uneventful and a revision did not take place in case numbers 9 and 33. In fact, cases 9 and 33 were marked as false positives.

Subgroup t2: Between 24 and 48 h, case 2 and 10 presented with further progressive venous congestion in their clinical and instrumental assessment and immediately underwent revision. The venous anastomoses of case numbers 2 and 10 presented with an occlusion and were thrombectomized and reanastomosed. Case 20 presented with a venous thrombosis of the accompanying flap veins. However, a second revision was not performed owing to overall poor prediction. Case 31 could no longer be measured. Case 41 was revised as mentioned above. Every case was marked as true positive.

Case 33 was indicated for major revision based on HSI findings. However, there were no clinical data regarding the signs of malperfusion, and case 33 was marked as false positive. By contrast, case 9 was no longer indicated for revision based HSI findings after 24 h and was marked as true positive.

Subgroup t3: Between 48 and 72 h after free-flap surgery, cases 4 and 26 had a prolonged recapitalization caused by venous congestion. Clinical and hyperspectral data indicated and confirmed venous congestion caused by venous thrombosis between 48 and 72 h postoperatively. The decision to discard the flap in both cases was validated owing to multiple thromboses. Both flaps required surgical debridement and either flap advancement or additional tissue reconstruction via a 2nd free flap. Cases 2, 10, 20, and 41 presented with progressive necrosis of the whole flap caused by secondary venous thrombosis. A second revision was not carried out. In contrast to the clinical findings, HSI provided unremarkable data in case numbers 10 and 20. That is why both cases were marked as false negatives.

In summary, 124 records were made within our study period. Of these 124 measurements, HSI showed poor flap perfusion in 14 records within 72 h. Seven flaps were lost in our study period (cases 2, 4, 10, 20, 26, 31, and 41). HSI accurately identified venous congestion in 11 of 14 assessments of free flaps. Three assessments were marked as false positive (case 9 and 33) and two assessments were marked as false negative (cases 10 and 20) (Fig. 4). Based on these data, the sensitivity and specificity of HSI were 84% and 97%, with the positive and negative predictive values of 78% and 98%, respectively (p-value < 0.001).

Discussion

A previous study showed that the success rate of microvascular free-tissue transfer is >90% [12]. Despite the good outcomes of head and neck surgery, the outcomes of older individuals and those with obesity and atherosclerosis are challenging to manage. If a malperfusion of a free flap takes place, a prompt reintervention improves flap salvage [13].

The technical noninvasive monitoring methods include NIR [14], laser Doppler flowmetry/tissue spectrophotometry [15], and HSI [11] (Table 2). NIR has been used clinically since 1995 [16], and it has several advantages. In a retrospective trial of 900 microsurgical breast reconstructions, NIR proved to significantly decrease the flap loss rate and improved the flap salvage rate [17]. In a second retrospective study of 1050 patients who underwent microsurgical tissue reconstruction, the rate of flap salvage increased to 96.6%, and the number of complete flap losses decreased. Even the rate of reintervention decreased over time [18]. In a systematic review, the overall flap success rate was 99.5%, and the flap salvage rate was 91.1% [14]. Otherwise, compared with laser flowmetry, NIR cannot predict wound complications, including fat necrosis [19], or provide information on blood flow [20].

Table 2
Different types of noninvasive monitoring devices

Method	HSI [6, 27]	NIR [14, 28]	Laser Doppler flowmetry/tissue spectrophotometry [15]
Device/company	Tivita Tissue®/Diaspective Vision, Germany	Tissue Oximeter®/T.Ox, the USA	O2C®LEA Medizintechnik, Germany
Range	500–1000 nm	690–850 nm	830 nm/500–800 nm
Modality	Noninvasive	Noninvasive	Noninvasive
Assessment frequency	Discontinuous	Every 2–4 s	Continuous
Monitoring modality	Imaging (30 × 30 cm]	No imaging (probe)	No imaging (probe)

Laser Doppler flowmetry, similar to the O2C device, can determine blood flow (flow), velocity, hemoglobin oxygenation, and relative hemoglobin concentrations [15]. Furthermore, the O2C device can provide data regarding intracapillary hemoglobin oxygenation in

correlation with intracapillary hemoglobin saturation and the local blood flow rate [15]. Vessel occlusion was detected in five of five patients who underwent free-flap breast reconstruction. Thus, O2C may improve flap survival rates at an early stage [15]. The disadvantage of the O2C device is its cost and cautious placement of sensor as shearing motions and excessive pressure can lead false measurements [15].

HSI and NIR are both optical devices measuring the tissue perfusion in different electromagnetic ranges. In contrast to O2C or NIR, HSI can facilitate a contact-free, noninvasive imaging analysis. In a recent systematic review, the most frequently reported limitations of clinical monitoring were need for expert interpretation (25% of related papers), unsuitability of buried flaps (21%), and a lack of quantitative/objective values (19%) [21]. To provide sufficient quantitative data and reduce the need for expert interpretation, different diagnostical studies were published to establish quantitative thresholds about HSI in microsurgical tissue reconstruction in recent years [8, 9, 11, 22, 23]. All studies have a prospective character, a low number of presented cases, and a re-exploration rate based on clinical assessments in common. Furthermore, every study postulated that malperfusion goes hand in hand with reduced oxygen saturation in form of a decreased StO₂ and NIR. Due to the low number of cases and the different kinds of flap surgeries, different thresholds were postulated (Table 3). However, a distinction between arterial occlusion and venous congestion was not made in every trial. So, the role of other parameters like the THI or TWI remains unclear.

Table 3
Various studies related to HSI and its diagnostic value.

author	Thiem et al. [9]	Thiem et al. [29]	Kohler et al. [8]	Schulz et al. [11]
year	2021	2020	2021	2021
design	prospective	prospective	prospective	prospective
cases	63	30	22	19
distinction between arterial occlusion and venous congestion	none	yes	none	yes
thresholds	StO ₂ ≤ 32% StO ₂ Δreference > -38% NRI ≤ 32.9 NRIΔreference ≥ -13.4%	StO ₂ < 40% NIR < 25% THI < 40%	NIR ≤ 40	THI ≥ 53% NIR ≤ 25% TWI ≤ 43% StO ₂ ≤ 22%

For the first time, our study has tried to move the role of the THI into the clinical focus and derive a therapeutic outcome from it. In the current study, HSI could predict poor tissue perfusion in all seven patients with total flap necrosis. Moreover, HSI confirmed adequate tissue perfusion in 108 of 124 measurements (specificity: nearly 97%). Only three measurements were documented as false positives and two as false negatives (sensitivity: approximately 84%). In the case of venous congestion, a decrease in StO₂ and NIR was observed in subgroups A, B, and C. However, it was only in the case of the NIR that this was statistically significant in contrast to the previous publications in Table 3. Otherwise, the THI was already statistically significant from subgroup A onwards to differentiate between vital and non-vital flaps as a dichotomous target variable. The diagnostic study presented here points out that in the case of venous congestion of the free flaps, the THI plays a role just as essential as the StO₂ or NIR. A high THI ≥ 53% seems to indicate a venous stasis. A simultaneous decrease in NIR and StO₂ suggests venous congestion or arterial occlusion [11].

One reason for the above-mentioned false positive results (cases 9 and 33) in our patient collective may be postoperative reactive hyperemia of both flaps. In both cases, the intraoperative anastomosis of a second vein was not taken into account. As a result, the venous flow may have increased compared with free flaps with two anastomosed veins, and a higher proportion of hemoglobin may have accumulated. An explanation for the two false positives assessments (case 10 and 20) may be that both assessments were taken between 48 and 72 h. Previously, there had been a prolonged malperfusion of both flaps that could explain the final drop in the THI as an expression of necrosis of the superficial skin tissue that had already begun.

The major role of HSI could be the early pre-clinical identification of flap compromises. Thiem et al. in a previous publication stated to detect perfusion compromises significantly earlier than clinical monitoring based on a decreased StO₂ or NIR [9]. The same would have to

be checked in regards to the THI. In case 41, HSI could report a revision indication within the first 24 h (t1). However, the clinical decision did take place on the following day. In this case, based on the HSI data, an earlier operational revision could have been initiated. However, due to the retrospective design of this study, this cannot be directly implemented and further prospective studies are necessary.

To create clarity and to be able to better control the massive amount of data, artificial intelligence could be a suitable alternative for predicting malperfusion. A large number of studies have been published in which diagnostic statements were made based on the data generated by the HSI. For example, different types of mouth tissue could be classified by their HS-signature using a deep learning approach [24]. Also, an algorithm for brain cancer classification [25] or for the differentiation between skin complications of diabetes mellitus and healthy volunteers using HSI and machine learning algorithms was demonstrated [26]. The further investigation of the flap perfusion by artificial intelligence seems to be possible and necessary. The lack of quantitative values mentioned at the beginning and the necessary interpretation for noninvasive flap monitoring devices could thus be remedied. Nonetheless, possible disadvantages of artificial intelligence are the large amounts of data that are required and the corresponding expense for programming.

The current study has several limitations. First, it was retrospective in nature. Moreover, because of the relatively small sample size, information regarding the areas of partial flap necrosis was not examined and there were missing data about flaps with arterial occlusion. Second, the measurements did not affect the usual clinical care; therefore, the flap salvage rate was not reproducible. The diagnostic value of postoperative assessment is, at least, defined by the flap salvage rate [17]. Fourth, the occurrence of late-onset complications, including wound edge necrosis, was not assessed [19].

Conclusions

HSI can detect impaired flap perfusion caused by venous stasis, which is defined as a THI of $\geq 53\%$. HSI could reasonably correlate with clinical observation. Up until now, HSI does not show any superiority over any other monitoring modality. THI as a marker for detection of malperfusion seem to be further assessed.

List Of Abbreviations

HSI Hyperspectral Imaging

STO2 Tissue oxygenation index

NIR Near-infrared perfusion index

THI Tissue hemoglobin index

TWI Tissue water index

ALT Anterolateral thigh

LDM Latissimus dorsi muscle

PSC Parcapular

DIEP Deep inferior epigastric perforator

NIRS Near-infrared spectroscopy

Declarations

ETHICS APPROVAL AND CONSENT TO PARTICIPATE

The ethics committee of the Ärztekammer Sachsen-Anhalt, Germany has approved the feasibility of the study prior to study initiation (Approval 35-17). In this study all patients signed a preoperative informed consent form and agreed to participate in the accompanying scientific research.

CONSENT FOR PUBLICATION

Not applicable

AVAILABILITY OF DATA AND MATERIALS

All data is contained within the manuscript. The datasets used and analyzed during the current study available from the corresponding author on reasonable request.

COMPETING INTERESTS

The authors declare that they have no competing interests.

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AUTHORS' CONTRIBUTIONS

All authors have made substantial contributions to the manuscript with respect to the conception and design of the study (TS, LK), acquisition of data and analysis (TS, RN, LK), interpretation of data (TS, LK), drafting the article (TS), and revising it critically for important intellectual content and have approved the final version of this manuscript (TS, RN, KH, SL, LK).

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Not applicable

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Figures

Figure 1

(A–G): Study protocol & case number 35. ALT flap for covering a defect on the left hand. (A) Study protocol (B) The TIVITA Tissue hyperspectral camera system. (C) The underlying flap was illuminated by a white light source. (D) An image was captured, and a marker was placed over the region of interest. (E) Average oxygenation of the tissue (StO_2) with a marker showing the concentrations of oxygen in the viable flap area. (F) Tissue hemoglobin index (THI). (G) Near-infrared (NIR) perfusion index.

Figure 2

(A–D): StO₂, THI, NIR, and TWI based on different perfusion status. (A) Decreasing StO₂ values of both groups. (B) Reduced NIR indicating venous congestion, requiring major revisions. (C) Increasing THI between venous congestion and viable free flaps.

Figure 3

(A–D): Case number 41. ALT flap for covering a defect on the right ankle. (A) Native image at t1. (B) Average THI with a marker demonstrating the relative amount of 53%. (C) Native image at t3. (D) Average THI at t3.

	Flap outcome avital	Flap outcome vital	
HSI avital	11	3	14
HSI vital	2	108	110
Sum	13	111	124
Sensitivity	0.84		
Specifity		0.97	p-value < 0.001

Figure 4

(A–J). HSI evaluation using a contingency table for each time point.