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RESEARCH ARTICLE

Early detection onset of flap failure using near infrared spectroscopy

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ABSTRACT

Background: Near-infrared spectroscopy (NIRS) is widely used to assess flap perfusions by measuring tissue oxygen saturation (StO_2). However, the StO_2 level for the onset of perfusion failure is still a controversial issue.
Aim: This study proposes a new threshold of StO_2 level for detecting the onset of perfusion failure as early as possible to increase flap salvage rates.
Methods: Twenty patients undergoing flap surgery were included in this study – 13 flaps were implemented to cover defects that occurred due to trauma and 7 flaps to hide imperfections that occurred after cancer treatment. Thirteen flaps were in the lower extremity, six in the mandible, and one in the breast. NIRS was used to measure StO_2 in 240 flap regions of the 20 patients to determine flap viability using descriptive statistics.
Results: The mean StO_2 values from healthy flap and control regions were obtained as 81.6% ± 0.36 and 82% ± 0.18, respectively. The lowest StO_2 value of 77.2% was defined as the onset of a vascular complication at a probability of 99.74% by subtracting three times the standard deviation from the mean StO_2 of healthy flaps. Vascular complications were observed from 21 regions in the four flaps with StO_2 values lower than 77.2%, but only one was lost.
Conclusion: The threshold value for the onset of perfusion failure was a 5% decrease from the expected value, much lower than previously described thresholds that may facilitate the detection of perfusion failure in the early stage and increase salvage rates in flap revisions.

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KEYWORDS
Detection of the onset of flap failure; perfusion failure; near-infrared spectroscopy; tissue oxygen saturation

1. Introduction

Flaps are commonly used in plastic surgery for the repair of complex tissue defects. Successful flap surgery depends on flap viability, and maintenance of microvascular blood flow and tissue oxygenation is therefore crucial. Flap compromise occurs in 5–25% of cases, usually in the first 72 h [1]. For flap salvage, flap viability can be secured by early detection of flap compromise or perfusion failure. The flap salvage rate is directly correlated with the amount of time elapsing from the onset of compromise to correction [2,3]. Flap monitoring traditionally involves clinical examination, i.e. skin color, the temperature of the flap, capillary refill, the pinprick test (needle puncture for checking the nature of bleeding), and turgor [4]. However, these evaluations depend on the surgeon's experience and may not be sufficient for early diagnosis. The subjective clinical examination may, therefore, delay the detection of flap compromise [5]. No objective gold standard method for monitoring of the flap has been available yet. Laser Doppler flowmetry [2], implantable Doppler probes [6], tissue oxygen tension measurement [7], and fluorescent angiography [8] techniques have all been investigated in the context of new flap assessment technologies.

Optical techniques have begun to be used for non-invasive, real-time, and less painful diagnosis in the early stages of disease [9,10]. In these techniques, visible-near infrared light (VIS-NIR) is sent to the tissue and diffuse back-reflected light is collected by an optical fiber probe and transmitted to a spectrometer. This provides a 'spectrum' of information about the tissue. The detected spectrum depends on the absorption and scattering of VIS-NIR light in tissue. The light absorbed by hemoglobin depends on the change in oxygen saturation. Tissue oxygen saturation (StO_2) can be determined by analyzing the absorption component of the light reflected from the tissue.

In near-infrared spectrometry (NIRS), StO_2 can be obtained by time-resolved, frequency domain, or steady-state domain measurements. Due to the simplicity and cost of the systems, steady-state and frequency domain measurements are more widely employed than time-resolved systems. However, StO_2 measurement values of healthy tissues with different devices are not consistent. For example, tissue oxygenation in a healthy individual was measured from the forearm as 68.10 ± 4.51 using a NIRO 200NX monitor (Hamamatsu, Japan) [11]. The Moxy Monitor (Fortiori Design LLC) NIRS device measured muscle tissue oxygen saturation at 67.9% ±9.9 [12]. The NIRS system (Oxiplex TS; ISS, Champaign, IL) is a frequency-domain multi-distance system that measured StO_2 at 71.9 ± 4.4 [13]. One of the applications of NIRS is monitoring StO_2 for post-op flaps. Therefore, in the absence of an absolute StO_2 value for healthy tissues, there is also no

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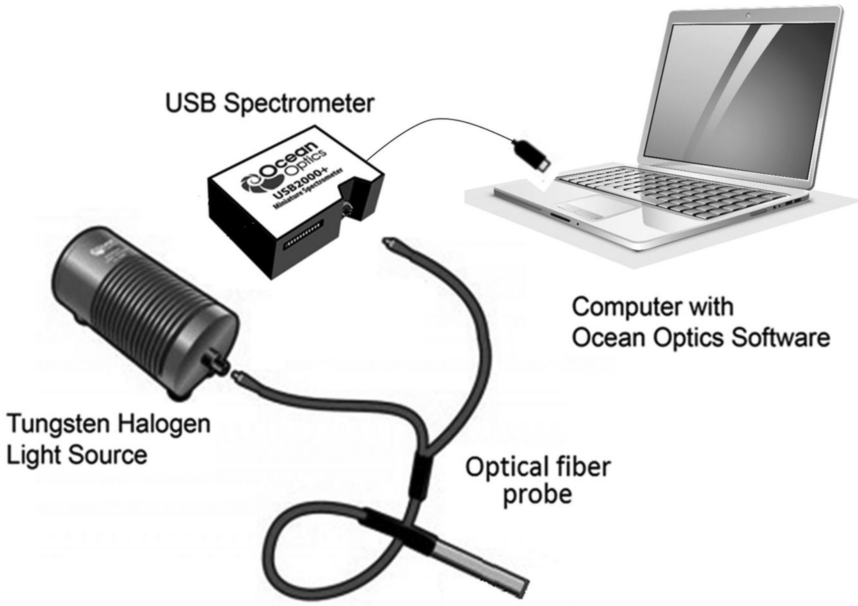

Figure 1. Schematic illustration of the VIS-NIR optical fiber spectroscopy system used *in vivo* to acquire spectroscopic data from the flap.

absolute StO_2 value for determining the onset of flap compromise. Onset of flap compromise has therefore been defined based on the percentage decrease in StO_2 according to reference values obtained from healthy tissue. However, the onset threshold values vary among different studies, and there is no defined onset value for early detection of flap compromise.

In the present study, StO_2 measurements acquired using NIRS from free flaps and control sites of tissues, and descriptive statistics were used to define the lowest percentage drop rate in StO_2 from reference values to establish a criterion for identifying the onset of perfusion failure.

2. Methods

2.1. Patients

The study was conducted at the Plastic and Reconstructive Surgery Departments, with the approval of the Institutional Review Board (the number of the ethics vote:70904504/220). All procedures followed were in accordance with the ethical standards of the responsible committee on human experimentation (institutional and national) and with the Helsinki Declaration of 1975, as revised in 2008. Informed consent was obtained from all patients for being included in the study. Spectroscopic measurements were acquired from 240 different regions of 20 flaps. Patients undergoing flap surgery were included prospectively from a single center.

2.2. Near-Infrared spectroscopy system

The NIRS system consisted of a miniature VIS-NIR spectrometer (Ocean Optics USB2000, FL), an optical fiber probe to deliver the light to and from the tissue (Visible-NIR reflection probe, Ocean Optics, FL), a halogen–tungsten light source (HL2000, Ocean Optics, FL), and a laptop computer. The optical fiber probe contained seven optical fibers with a core diameter of 400 μm arranged with one at the center and the other six surrounding it. The six surrounding fibers delivered the light to the tissue, while the central fiber detected the diffuse light reflected from the tissue. Figure 1 depicts a schematic illustration of the system.

The tip of the optical fiber probe was placed in contact with the flap for the spectroscopic measurements. The spectroscopy system was calibrated before acquiring the data from the flap, as previously described elsewhere [14].

Light at wavelengths of 760 nm and 790 nm is more absorbed by hemoglobin than water, melanin, and fat [15]. Light scattering decreases as wavelengths increase but does not change significantly between 760 and 790 nm [16]. The intensities of the back-reflected light are therefore strongly dependent on the concentrations of oxyhemoglobin and deoxyhemoglobin. In this study, back-reflected light intensities were measured from the flap at wavelengths of 760 and 790 nm, and the StO_2 values were estimated as previously described elsewhere [14].

2.3. StO_2 measurements

StO_2 was measured using NIRS for five days in the postoperative period. The first measurement was taken immediately after the flap anastomosis. Further measurements were performed on the first (every two hours), second (every four hours), third (every eight hours), fourth (twice a day), and fifth (twice a day) postoperative day. Each average StO_2 value was obtained over the eight spectroscopic measurements at the same location. The optical fiber probe was relocated to the region of interest for each spectroscopic measurement. In spectroscopic measurements, flaps were divided into four parts, and the measurements were taken from three different locations in each part. Thus, spectroscopic measurements were acquired from 12 different points in each flap within 12 min. Control measurements were made from healthy and non-operated tissue on the contralateral side of the defect area. The duration of the monitoring depended on the individual cases but lasted at least 120 h. At the end of the 120 h, if the physician decided that the flap was healthy, the measurements were terminated. However, if there were any complications in the flap, the measurements continued. Clinical follow-up continued for 5 days. The concept of flap compromise includes arterial or venous compromise, thrombosis, occlusion or excessive edema, wound infection, and wound separation [17]. These complications may require treatment or flap revision, but vascular

Table 1. Gender, average age, and flap recipient site distribution of the patients.

		Flap recipient site		
Gender	Average age	Lower extremity	Head and neck	Breast
Women (6)	45 ± 12	2	3	1
Men (14)	44 ± 11	11	3	–

compromise may eventually progress to an irreversible and total loss of the flap.

2.4. Statistical analysis

StO_2 values were expressed as mean ± standard deviation. Descriptive statistics were used to define the distribution of StO_2 values of 219 healthy flap locations based on the post-op time. StO_2 values of the control and normal flaps were evaluated using the independent samples *t*-test by setting statistical significance at 5% ($p < 0.05$). The analysis was performed on SPSS software version 17.0 (SPSS Inc., Chicago, IL).

3. Results

The spectroscopic data were acquired from 20 patients (six women and 14 men), with a mean age of 44 years (minimum 18, maximum 70). Patients' gender, average age, and distributions of flap recipient sites are given in Table 1. Clinical diagnosis and type of flap distribution of the patients are shown in Table 2. The data were acquired from 240 different regions ($n = 240$) of 20 flaps. The flaps were evaluated, with clinical examination as the gold standard. Microvascular reconstruction with flaps was performed successfully (healthy flaps) in 16 of the 20 cases, and no complications were observed in the flaps (192 healthy flap regions). Physicians diagnosed vascular complications in the distal part of the three flaps (only one of the four measurement parts in each flap). In total, nine spectroscopic measurements were acquired from different regions of the flaps with vascular complications. The measurement values obtained from the other three parts of these flaps were recorded as the healthy flap region (27 healthy flap regions). One of the flaps had a total failure, 12 spectroscopic measurements were acquired on it. So, in total, 219 measurements were obtained from healthy flap regions and 21 from flap regions with perfusion defects based on anastomosis failure or vascular complications. At the end of 5 days of clinical follow-up, the mean measured StO_2 values from the healthy flap regions and the control regions were 81.6% ± 0.36 and 82% ± 0.18, respectively. The difference was not statistically significant ($p > 0.05$). Physicians diagnosed a total flap failure by visual inspection and pinprick tests.

Spectroscopic evaluation of the flaps was processed in two steps. In the first step, a threshold value of StO_2 for flap vascular complications was defined based on the measurements acquired from the healthy flaps. In the second step, StO_2 values of the four flap regions with vascular complications were evaluated based on the defined threshold value.

StO_2 was found to exhibit a Gaussian distribution for each measurement time in the 219 healthy flap locations. The mean and standard deviation (σ) StO_2 values for each measurement time were then obtained for the healthy flap and the control regions. StO_2 values measured initially from the healthy flaps were slightly lower than those for the control regions, as seen in Figure 2(a). The Gaussian distribution curve of the second measurements over the 219 flap regions was determined. The mean $\pm 3\sigma$ covers 97.4% of the healthy tissue StO_2 values change between 77.19% and 85.05%. The lower bound of the StO_2 was obtained by subtraction of 3σ from its mean value (81.12%) for the all StO_2 measurements of healthy flaps. The measured StO_2 and the lower bond data are shown in Figure 2(b). On the lower bond graph, the second data point is 77.19%, which is a minimum over the entire post-op measurement time. A StO_2 value below 77.19%, thus, defines flap compromise with a probability of 99.74%. Tissue oxygen saturation of 77.19%, therefore, represents the onset value of the flap complication.

3.1. Flap with perfusion failure

Perfusion failures were detected in four cases by NIRS measurements and the physician's examination. Two of them were in the distal part of two flaps (patients 2 and 15). These two flaps were monitored clinically for a while, after which the flaps were successfully revised. The distal part of the flaps was resected, and both survived. The spectroscopic measurements for both patients were similar. Only the data obtained from patient 15 is, therefore, presented below.

Postoperative StO_2 values for patient 15 for the distal part of the flap, the other side of the flap, and the control region are shown in Figure 3. Physicians diagnosed distal venous complications after 24 h of clinical follow-up based on visual skin color and capillary refill examinations. Mean StO_2 values at 24 h were 81% in the control region, 69% in the distal part of the flap, and 81% on the other side of the flap (Figure 3). At the end of the fifth day, StO_2 values were 82% in the control region, 58% in the distal part of the flap, and 82% on the other side of the flap. At the end of the five-day clinical follow-up, the physicians decided to resect the distal part of the flap. After revision, StO_2 values measured in the distal part were similar to those in the control region.

In one of the perfusion failures, venous congestion occurred in the distal part of the flap (patient 4). StO_2 values at the second measurement were 82% in the control region, 73% in the distal part of the flap, and 83% on the other side of the flap (Figure 4). These values indicated vascular complications in the distal portion of the flap at the second measurement. The physicians revised the sutures to ensure venous drainage before the third measurement. After that procedure, StO_2 values immediately became identical to those in the control region in the distal part of the flap.

One total flap failure occurred despite re-exploration (patient no. 10), as seen in Figure 5. Hematoma and edema developed in all parts of the flap, and the patient was re-operated at the post-op 23rd hour. During the operation, the hematoma was drained, the superficial venous lumen ligated, the leaks cauterized, and the leaks in the arterial anastomosis revised. However, the vascular complications in the flap continued. Postoperative flap and control region StO_2 values are shown in Figure 6. At the 25th hour of clinical follow-up, the patient was re-operated due to hematomas and edema. These were evacuated, and the arteries and veins were revised. StO2 measurement at the 28th hour was not possible since the patient was undergoing surgery. The first StO_2 measurements after the revision were acquired in the 32nd hour, 83% in the control region and 72% in the flap. At the end of the 5-day clinical follow-up, the patient was re-operated, but flap compromise occurred due to circulatory complications.

The onset of the vascular complications for patients 2, 15, and 10 ($StO_2 < 77.19\%$) were detected 4 h after anastomosis by NIRS.

Table 2. Clinical diagnosis and type of flap distribution of the patients.

	Type of Flap		
Clinical diagnosis	Anteorlateral thigh perforator flap	Musculocutaneous flap	Osteomuskulocutaneous flap
Trauma (13)	12	1	–
Cancer (7)	2	1	4

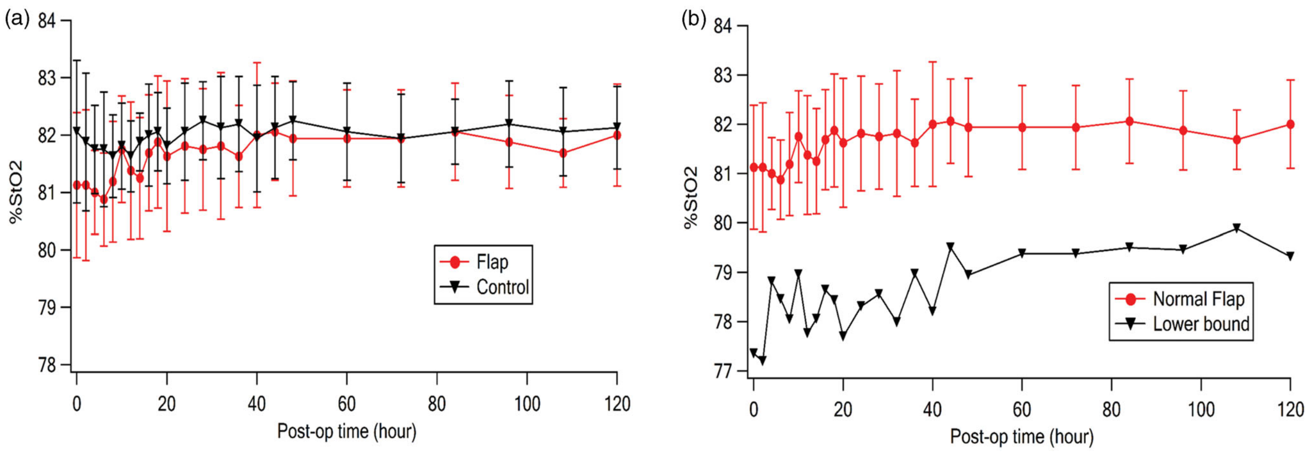

Figure 2. (a) The StO_2 values of healthy flap and control (average of 16 patients) over 120 h. (b) Measurements from the flap and its lover bond obtained by subtracting 3σ from each data point. As seen on the lower bond graph, the second value is the lowest one and taken as the lowest StO_2 value of the normal flaps.

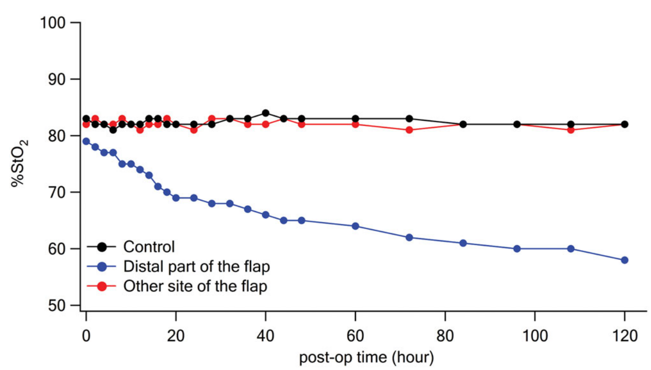

Figure 3. StO_2 values of the distal part of the flap, another site of the flap, and control of patient no. 15.

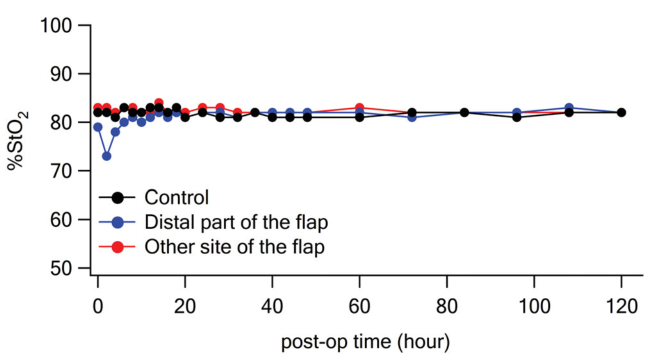

Figure 4. StO_2 values of the distal part of the flap, another site of the flap, and control (patient no. 4).

The perfusion complications were diagnosed by physician's examination 24 h after flap anastomosis in patients 2, 15, and 10. The time elapsed between the NIRS detection of perfusion failure and clinical diagnosis was 20 h for all three patients. The vascular complication was detected at the second measurement in patient 4, 4 h after anastomosis based on a StO_2 measurement of 73%.

4. Discussion

There are many monitoring techniques for the detection of circulatory problems in a free flap. Hand-held Doppler ultrasonography, color duplex ultrasonography, fluorescent angiography, implantable Doppler, and laser Doppler flowmetry (LDF) are techniques that monitor vascular flow. Infrared spectroscopy (NIRS) and microdialysis are techniques to monitor tissue metabolism and ischemia. Among numerous monitoring methods, The NIRS tissue oximeter has been reported as a useful technique because it is reliable, non-invasive, and provides continuous monitoring. Many studies were conducted, and some devices were developed to measure tissue oxygen saturation using NIRS in the assessment of flap perfusion. Commercial examples of NIRS tissue oximeter include the ViOptix T.Ox (ViOptix, Newark, CA) and InSpectra Model 325 (Hutchinson Technology Inc., Hutchinson, MN). Koolen et al. reported a study with 680 NIRS-monitored flaps compared with 380 control free flaps in breast reconstruction. This study found that the flap loss rate using NIRS was 0.1% compared with 2.9% in the control group [18]. However, NIRS devices used in StO_2 measurements have yielded inconsistent values for healthy

Figure 5. A total flap failure at the end of the five-day clinical follow-up of a patient (patient no. 10).

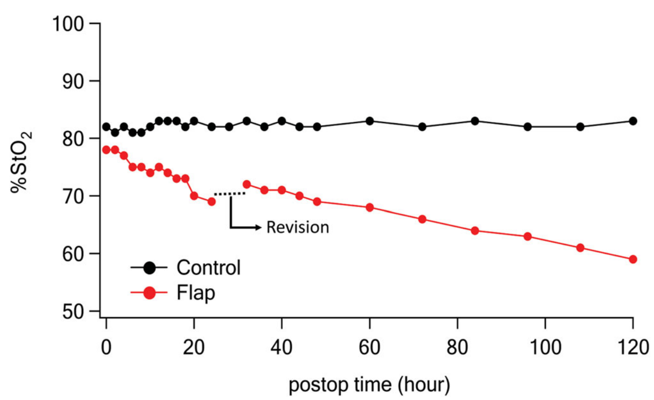

Figure 6. StO_2 values of the flap and its control of a patient (patient no. 10) for 120 h.

tissues (11–14, 22). The conflicting StO_2 values generated by different NIRS devices may be due to other calibration methods, probe source-detector separations, or measurement locations [11–13,19,20].

Since there is no absolute value for healthy tissue oxygen saturation, there is no absolute onset of StO_2 value for perfusion defects. . Therefore, several criteria have been determined in the literature to establish the beginning of vascular complications based on a decreasing percentage from reference values measured from the healthy tissue. Most authors have used a criterion described by Keller [19], in which vascular problems were evaluated using an oxygen saturation reading threshold less than 30% or a drop rate greater than 20% per hour exceeding 30 min in duration [21]. Rapes et al. defined a drop of 50% from the reference value for flap revision [20]. Steel reported tissue oxygenation values of less than 40% or a drop rate in tissue oxygen saturation greater than 15% per hour [22]. Akita et al. defined the onset tissue oxygen saturation for flap compromise as a 25% drop from the reference value [23]. The flap salvage rate is high for all these different criteria. However, it is still unclear whether the specified criteria provide the earliest sign of vascular compromise.

In the present study, the healthy tissue StO_2 value was 82%. In the case of a flap StO_2 value lower than 77.19%, there is a 99.74% probability of perfusion problem. A 5% drop from healthy tissue oxygenation StO_2 levels results in perfusion failure. This drop rate of 5% is much lower than the previously reported drop rates listed above. We regard a 5% decrease in StO_2 standard values indicating the onset of perfusion failure at a probability of 99.74%.

NIRS measurements in the present study were acquired from the flap peripheries. Detection of peripheral perfusion defect may be an early sign for needing a revision such as a suture release and hematoma drainage. Therefore, the measurements were acquired from the peripheries of the flap. Since the NIRS device is user-friendly and not time-consuming, it is helpful to apply to several flap locations. Since perfusion defects based on anastomosis failure usually start at the most distal part of the flap in the very early stage, using the probe on the best-perfused part of the flap, as described by Arnez et al. (7) may not provide useful information concerning the detection of vascular problems in the early phase. During the present study, we, therefore, monitored several sites to identify locations with insufficient blood perfusion. Obtaining measurements from several parts of the flap may increase the possibility of detecting early vascular or nonvascular complications. The technique is quite useful for non-buried flaps. The device is user-friendly, and a nurse can use it for clinical monitoring after 5–10 min of training. The device acquires data within 1 second and is, thus, also suitable for assessing buried flaps.

One of the limitations of the study is the absence of continuous measurements. Another one is performing the spectroscopic measurements only on four flaps with a lack of perfusion. One of them was failed due to vascular compromise. The other three had only flap defects based on anastomosis failure were revised. Besides them, the measured tissue oxygen saturation may be change based on the distance between the source-detector separation of a NIRS probe and the tissue location where the measurements were acquired. Hence, more extensive clinical studies should now be conducted for a more definite conclusion.

5. Conclusion

Early detection of flap perfusion defect and adequate oxygenation correlated with salvage rates. The threshold value for the onset of perfusion failure is defined as a drop of 5% from its expected value. The proposed criterion may have the potential to indicate early revision and increase salvage rates in the clinical setting.

Disclosure statement

No potential conflict of interest was reported by the authors.

Grant information

The study was approved by the Akdeniz University Institutional Review Board (24.03.2013/122). All procedures followed were in accordance with the ethical standards of the responsible committee on human experimentation (institutional and national) and with the Helsinki Declaration of 1975, as revised in 2008. Informed consent was obtained from all patients for being included in the study

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References

[1] Chen KT, Mardini S, Chuang DCC, et al. Timing of presentation of the first signs of vascular compromise dictates the salvage outcome of free flap transfers. Plast Reconstr Surg. 2007;120(1):187–195.
[2] Yuen JC, Feng ZL. Reduced cost of extremity free flap monitoring. Ann Plast Surg. 1998;41(1):36–40.
[3] Hirigoyen MB, Urken ML, Weinberg H. Free flap monitoring: a review of current practice. Microsurgery. 1995;16(11):723–726.
[4] Evans GRD. Operative plastic surgery. Beverly Hills (CA): McGraw-Hill; 2000.
[5] Lin SJ, Nguyen MD, Chen C, et al. Tissue oximetry monitoring in microsurgical breast reconstruction decreases flap loss and improves rate of flap salvage. Plast Reconstr Surg. 2011;127(3):1080–1085.
[6] Ferguson REH, Yu PR. Techniques of monitoring buried fasciocutaneous free flaps. Plast Reconstr Surg. 2009;123(2):525–532.
[7] Arnez ZM, Ramella V, Papa G, et al. Is the LICOX® PtO2 system reliable for monitoring of free flaps? Comparison between two cohorts of patients. Microsurgery. 2019;39(5):423–427. Epub 2018/12/05.
[8] Pestana IA, Coan B, Erdmann D, et al. Early experience with fluorescent angiography in free-tissue transfer reconstruction. Plast Reconstr Surg. 2009;123(4):1239–1244.
[9] Jerjes W, Swinson B, Pickard D, et al. Detection of cervical intranodal metastasis in oral cancer using elastic scattering spectroscopy. Oral Oncol. 2004;40(7):673–678.
[10] Karakaş BR, Sı rcan-Küçüksayan A, Elpek Ö, et al. Investigating viability of intestine using spectroscopy: a pilot study. J Surg Res. 2014;191(1):91–98.
[11] Abay TY, Kyriacou PA. Comparison of NIRS, laser Doppler flowmetry, photoplethysmography, and pulse oximetry during vascular occlusion challenges. Physiol Meas. 2016;37(4):503–514. Epub 2016/03/11.
[12] Feldmann A, Schmitz R, Erlacher D. Near-infrared spectroscopy-derived muscle oxygen saturation on a 0% to 100% scale: reliability and validity of the Moxy Monitor. J Biomed Opt. 2019;24(11):1–11. Epub 2019/11/20.
[13] McLay KM, Gilbertson JE, Pogliaghi S, et al. Vascular responsiveness measured by tissue oxygen saturation reperfusion slope is sensitive to different occlusion durations and training status. Exp Physiol. 2016;101(10):1309–1318. Epub 2016/07/20.
[14] Sircan-Kucuksayan A, Uyuklu M, Canpolat M. Diffuse reflectance spectroscopy for the measurement of tissue oxygen saturation. Physiol Meas. 2015;36(12):2461–2469.
[15] Barolet D. Light-emitting diodes (LEDs) in dermatology. Semin Cutan Med Surg. 2008;27(4):227–238.
[16] Jacques SL. Optical properties of biological tissues: a review. Phys Med Biol. 2013;58(11):R37–R61.
[17] Whitaker IS, Pratt GF, Rozen WM, et al. Near infrared spectroscopy for monitoring flap viability following breast reconstruction. J Reconstr Microsurg. 2012;28(3):149–154.
[18] Koolen PGL, Vargas CR, Ho OA, et al. Does increased experience with tissue oximetry monitoring in microsurgical breast reconstruction lead to decreased flap loss? The learning effect. Plast Reconstr Surg. 2016;137(4):1093–1101.
[19] Keller A. A new diagnostic algorithm for early prediction of vascular compromise in 208 microsurgical flaps using tissue oxygen saturation measurements. Ann Plast Surg. 2009;62(5):538–543.
[20] Repez A, Oroszy D, Arnez ZM. Continuous postoperative monitoring of cutaneous free flaps using near infrared spectroscopy. J Plast Reconstr Aesthet Surg. 2008;61(1):71–77.
[21] Chen Y, Shen ZZ, Shao ZM, et al. Free flap monitoring using near-infrared spectroscopy: a systemic review. Ann Plast Surg. 2016;76(5):590–597.
[22] Steele MH. Three-year experience using near infrared spectroscopy tissue oximetry monitoring of free tissue transfers. Ann Plast Surg. 2011;66(5):540–545.
[23] Akita S, Mitsukawa N, Tokumoto H, et al. Regional Oxygen Saturation Index: a novel criterion for free flap assessment using tissue oximetry. Plast Reconstr Surg. 2016;138(3):510e–518e. Epub 2016/08/25.