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ARTICLE

Perfusion dynamics of the medial sural artery perforator (MSAP) flap in lower extremity reconstruction using laser Doppler perfusion imaging (LDPI): a clinical study

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ABSTRACT
Perforator flaps are a mainstay in reconstructive surgical practice but are limited by complications, including flap failure, resulting from flap hypoperfusion. This study aimed to characterize the early post-operative perfusion dynamics of the medial sural artery perforator (MSAP) flap in lower extremity reconstruction using laser Doppler perfusion imaging (LDPI). 12 patients, recruited between 2014 and 2015, with lower extremity reconstructions using free MSAP flaps were assessed for perfusion using a hand-held colour Doppler ultrasound device on days 1, 3, and 5 post-operatively. Perfusion at four distinct zones was assessed; whole flap, control zone, perforator zone, and distal zone, by a single operator using a standardized technique. The perforator zone was noted to have the highest relative perfusion of all zones measured across all post-operative days, and this was correlated with whole flap perfusion ($r = 0.82$, $p = 0.002$). No significant perfusion differences were found within any of the zones over the 5-day period. The perfusion at the distal zone was not found to correlate with either the perforator zone perfusion, flap length, flap length to width ratio or smoking status ($p > 0.05$). Perfusion of the MSAP flap can adequately be monitored using LDPI at any point throughout the flap, though is highest at the perforator zone, and remains constant in the early post-operative period.

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Introduction

In the last decades, perforator flaps have evolved as one of the most popular reconstructive options across a range of pathologies and body sites, owing to better cosmetic outcomes and patient satisfaction, and reduced donor site morbidity [1]. Detailed knowledge of the vascular anatomy of these perforator flaps, and their clinical implications has been extensively described, and is based on the angiosome theory of tissue transfer - itself the result of observations on serial cadaveric studies [2,3]. Despite greater advancements in microsurgical techniques, there remains significant variability in the circulatory dynamics of these perforator flaps during the postoperative phase, with obvious consequences for tissue, and thus flap, survival.

Recently, perfusion dynamic studies have been utilized to better characterize the perfusion of these flaps in order to understand their perfusion zones and so improve flap outcomes [4–6]. However, the majority of these studies have focused on the deep inferior epigastric perforator (DIEP) flap, the commonest flap in breast reconstruction. This has led to a paucity in the literature regarding the perfusion dynamics of other widely used flaps such as the anterolateral thigh (ALT), the medial sural artery perforator (MSAP), and the superficial circumflex iliac perforator (SCIP) flaps. Of note, none of these flaps cross the midline, and there are no clear anatomical landmarks to delineate their vascular territory, as exists in the case of the DIEP flap. Due to the limited understanding of their haemodynamics and microcirculation, it is difficult to predict which part of the perforator flap may be susceptible to necrosis from ischemic changes in the postoperative period [4].

A range of techniques to assess perfusion dynamics has been described in the literature, one of which is laser Doppler perfusion imaging (LDPI). LDPI allows accurate quantification and visualization of skin blood flow by non-invasive means, through utilizing the Doppler principle from a laser shone into a flap, to derive the speed of blood flow and thus tissue perfusion. Furthermore, this novel technique allows us to study flap perfusion hemodynamics *in vivo*, and integrates blood flow readings from a considerably large area [7,8]. It has been successfully used in monitoring different flap perfusion zones and evaluation of microcirculatory changes in several previous studies, and has been shown to improve clinically relevant end points such as flap salvage and survival rates [9–13].

This study aims to describe the topographic and temporal vascular changes within the MSAP flap during the early postoperative period in patients who undergo extremity reconstruction, and to evaluate the different factors that predict the perfusion reliability of the distal segment of this flap. Our hypothesis is that there are

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unique perfusion characteristics in distinct zones of the flap in the immediate postoperative period.

Methods

Study design

In this prospective observational study, microcirculatory changes within the MSAP flap were evaluated using LDPI in patients undergoing reconstructive surgery for soft tissue defects of the extremities. The local ethical committee approved the research protocol, and the study conducted as per the World Medical Association Declaration of Helsinki (1964).

Patient data

Between 2014 and 2015, 22 patients undergoing extremity reconstruction with an MSAP flap were recruited from a single center. Demographic and health factors for patients were recorded, including: gender, age, BMI, smoking status and presence of peripheral vascular disease. Exclusion criteria included if the flap was not suitable for accurate laser Doppler recording due to flap inset or use of external fixator, incomplete data sets, and if patients were not cooperative.

Surgery

All patients underwent a standard MSAP flap as described by Lin et al., with the flap and recipient area being prepared simultaneously [14]. With the patient supine, the ipsilateral leg is abducted and the knee flexed to 90 degrees. The perforators are identified along a line drawn from the midpoint of the popliteal crease to the medial malleolus, using a hand-held Doppler ultrasound. The perforator is identified *via* an anterior skin incision and traced intramuscularly in a retrograde fashion to the medial sural artery. The vascular pedicle was dissected proximally to achieve the required length and caliber. The whole flap was transferred to the recipient area, microanastomosis performed with the recipient vessel, and the flap trimmed and inset, whilst the donor site was closed. Specific operative data recorded included: width and length of flap skin paddle, number of perforators, recipient vessel, ischemia time and location of defect.

Post-operatively, the patient was monitored on a dedicated microsurgery intensive care unit according to standard departmental protocols, which included strict bed rest for up to 7 days post-operatively, active patient warming, and careful fluid balance monitoring.

LDPI measurement

A LDPI machine was used to monitor the microcirculatory changes in the skin of the MSAP flap. The principles of laser Doppler have been described elsewhere, but briefly, it consists of a beam of low power laser light reflected onto a tissue surface through an optical fibre. Blood cells traversing this light cause a shift in the frequency of light (Doppler effect), which is interpreted as a blood perfusion measure by the machine, and can then be used to construct a colour map of blood flow [15]. Each flap underwent LDPI measurement at four distinct zones: *control zone* (a healthy area away from the flap without any incisions or trauma), *perforator zone* (a square of 10 to 15mm^2 around the perforator), *distal zone* (a square of the same size as the perforator zone in the most distal part of the flap) and the *whole flap* (Figures 1 and 2(A–D)). The length and the width of the skin paddle taking the perforator as the origin point was measured for each flap (Figures 1 and 2(E–F)).

Perfusion measurements of the four zones (Control, Perforator, Distal and Whole flap) were obtained using the LDPI machine on day 1, 3 and 5 post operatively (i.e. POD 1, 3, and 5 respectively). The same author performed all of the measurements with the patient supine. The warming lamp was discontinued for a minimum of 5 min prior to scanning to ensure the recipient site was at room temperature. The device to skin distance was set at 40 cm, and all scans were done perpendicular to the flap.

Statistical analysis

Non-parametric analysis was used due to sample size. The Mann-Whitney test was used to compare two medians of continuous variables whereas Kruskal-Wallis was used to compare three or more medians of continuous variables. Dunn's multiple comparison test was used *post hoc* to analyze specific samples for stochastic dominance. Correlations between relative perfusion and different factors (e.g. ratio of flap, post operative day) were performed using Spearman's rho correlation. All of the statistical tests were two-sided and were performed with Prism 5 for Mac OS, version 5.0c (GraphPad Software Inc. La Jolla, CA). Statistical significance was considered when $p < 0.05$.

Results

A total of 22 patients were initially enrolled in the study, although only 12 met the inclusion criteria for subsequent analysis. Reasons for exclusion were: inability to perform LDPI ($n = 7$), incomplete data recording ($n = 8$), and non-cooperative patients ($n = 2$).

Table 1 shows the demographic data for the included patients. 5 female and 7 male patients, with an average age of 34.9 years

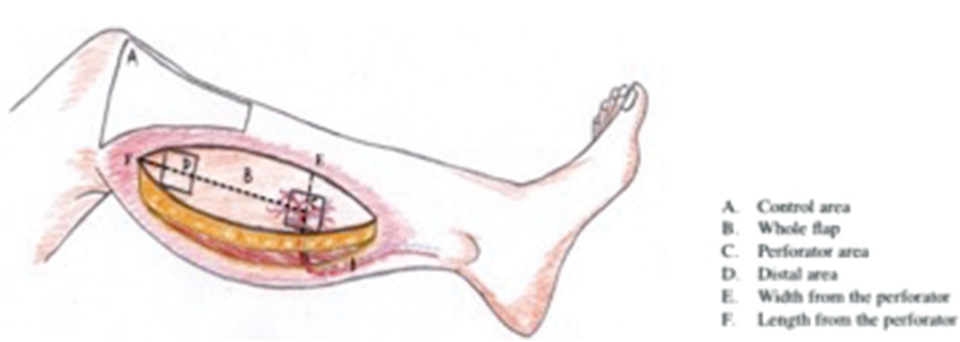

Figure 1. Schematic representation of the LDPI measurement protocol.

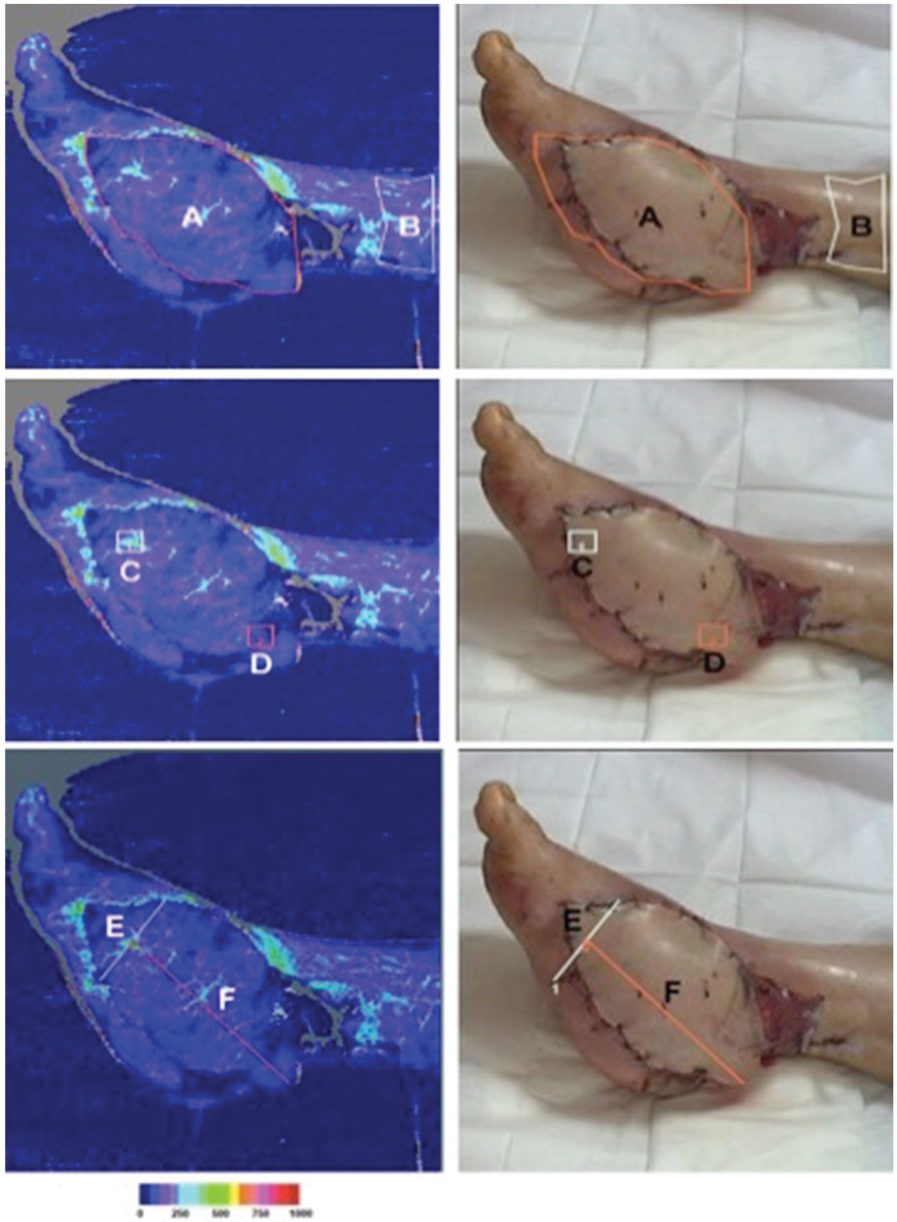

Figure 2. Laser Doppler images (left) and clinical photographs (right) illustrating; Whole flap zone (A), Control zone (B), Distal zone (C), and Perforator zone (D). The width (E) and length (F) of the perforator flap skin paddle was identified as shown.

Table 1. Demographic and operative data for included patients in the study.

Patient	Age	Gender	Smoking status	Comorbidities	Perforator number	Recipient vessel
1	39	M	No	N/A	2	ATA[b]
2	67	F	No	CVA[a]	2	PTA[c]
3	26	M	Yes	N/A	2	DPA[d]
4	50	M	No	Hypertension, Diabetes Mellitus	1	ATA
5	19	M	No	N/A	1	PTA
6	57	F	Yes	Hypertension	2	PTA
7	50	F	Yes	N/A	1	DPA
8	27	M	No	N/A	2	DPA
9	20	M	No	Hypertension	2	PTA
10	20	F	No	N/A	2	PTA
11	43	M	Yes	Diabetes Mellitus	2	PTA
12	25	F	No	N/A	3	ATA

[a]CVA: Cerebrovascular accident; [b]ATA: Anterior tibial artery; [c]PTA: Posterior tibial artery; [d]DPA: Dorsalis pedis artery.

(range = 19–67 years) were included. 4 out of 12 patients presented smoking habit. 5 patients suffered medical co-morbidities such as high blood pressure, cerebrovascular accident and diabetes mellitus.

All cases involved lower limb reconstruction following trauma ($n = 12$), and reconstruction was based on a free flap design. Flaps were based on a single perforator in 3 cases, on two perforators in 8 cases and on three perforators in 1 case. The mean

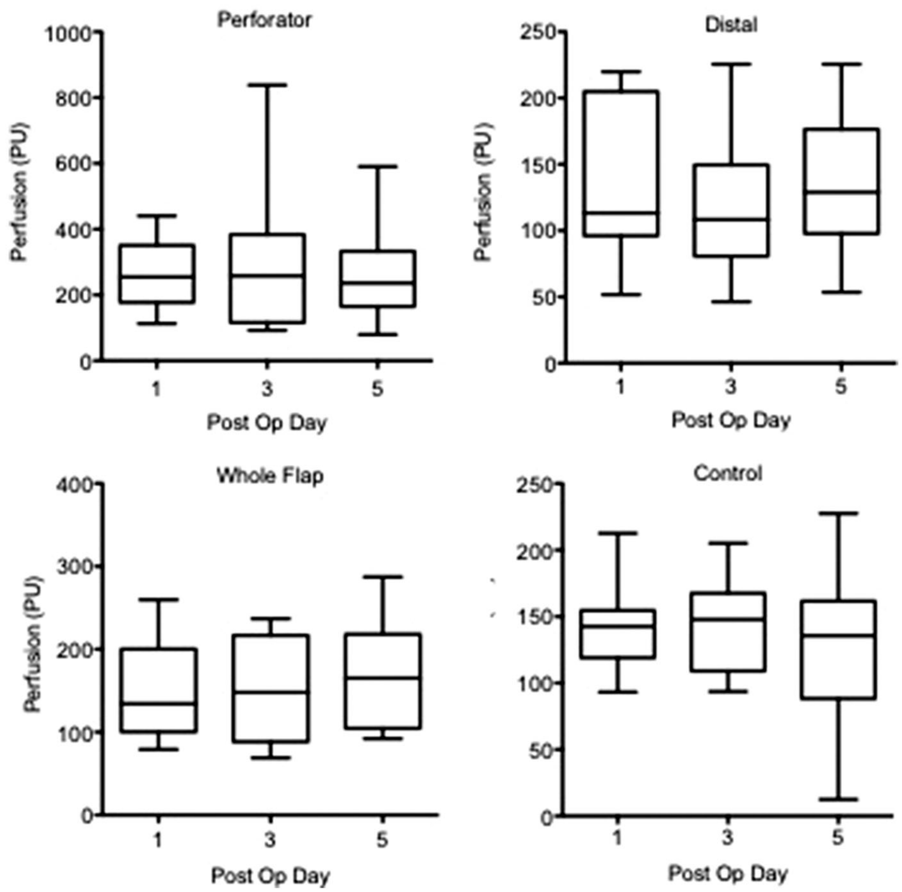

Figure 3. Perfusion of each of the four zones at POD1, 3, and 5 respectively.

and standard deviation (SD) of the width of the skin paddles was 5.93 ± 1.01 cm and the mean and SD of the length was 12.48 ± 2.05 cm. The length:width ratio was 2.1, ranging from 0.98 to 3.17. There were no recorded complications, and all flaps survived.

With regards to flap perfusion, there was no statistically significant difference in intra-zone perfusion within any zone between POD 1, 3, and 5 (Figure 3 below). Although, the relative perfusion of the distal zone and whole flap increased with increasing number of days post-operatively, this did not reach statistical significance.

Comparing inter-zone perfusion, the perforator zone had the highest relative perfusion when compared to the control zone, distal zone and whole flap over all post op days measured (Figure 4). The distal zone had a lower perfusion than the control area in POD 1 and POD 3, though this difference disappeared by POD 5. The whole flap showed very little difference in perfusion from the control zone during POD 1 and POD 3, and a mildly higher overall perfusion by POD 5.

There was a positive linear correlation between perforator and whole flap perfusion on POD 1 and POD 5 ($r = 0.61$, $p = 0.04$ and $r = 0.82$, $p = 0.002$ respectively) (Figure 5). Surprisingly, perfusion in the distal zone also showed a positive correlation with whole flap perfusion on POD 1 ($r = 0.60$, $p = 0.0043$). Although this positive correlation continues even on POD 5, it was not statistically significant ($r = 0.57$, $p = 0.059$) (Figure 6). Despite this, there was no correlation between the level of perfusion at the perforator zone and the distal zone on either POD 1 and POD 5 ($r = 0.112$, $p = 0.733$ and $r = 0.238$ and $p = 0.457$ respectively) (Figure 7).

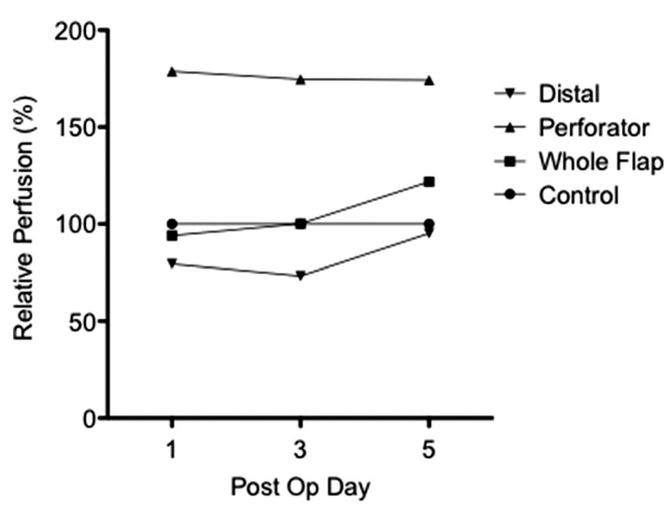

Figure 4. Comparison of the relative perfusion of the four zones over POD1, 3, and 5 respectively.

In contrast, there was only a small but not significant negative correlation between the perfusion of the distal zone and the length of the flap (Figure 8), whilst no correlation was found between perfusion of the distal zone and the length:width ratio of the flap (Figure 9), at both POD 1 and POD 5.

Discussion

Free tissue transfer using perforator flaps has become established as the mainstay for plastic and reconstructive surgical procedures

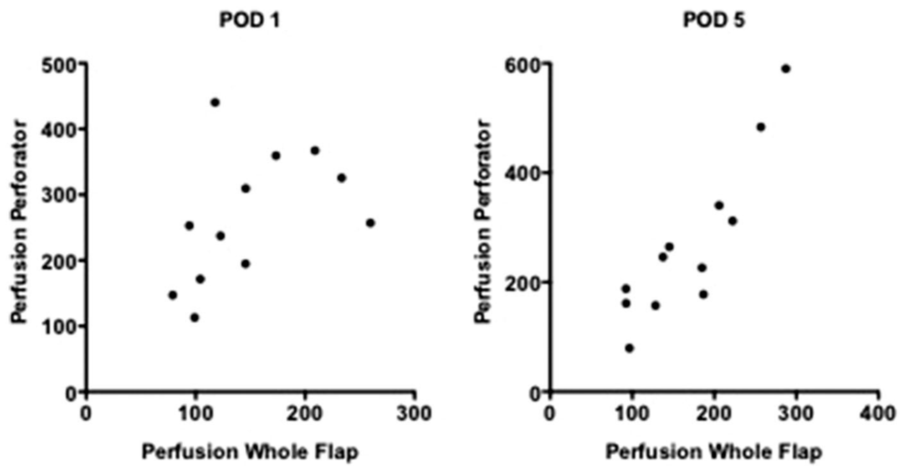

Figure 5. Correlation between Perforator zone and Whole flap perfusion at POD 1 (left) and POD 5 (right).

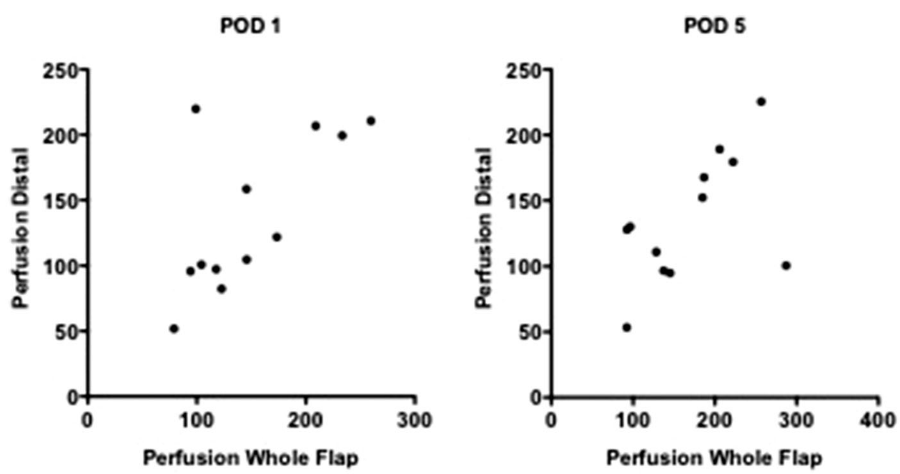

Figure 6. Correlation between Distal zone and Whole flap perfusion at POD 1 (left) and POD 5 (right).

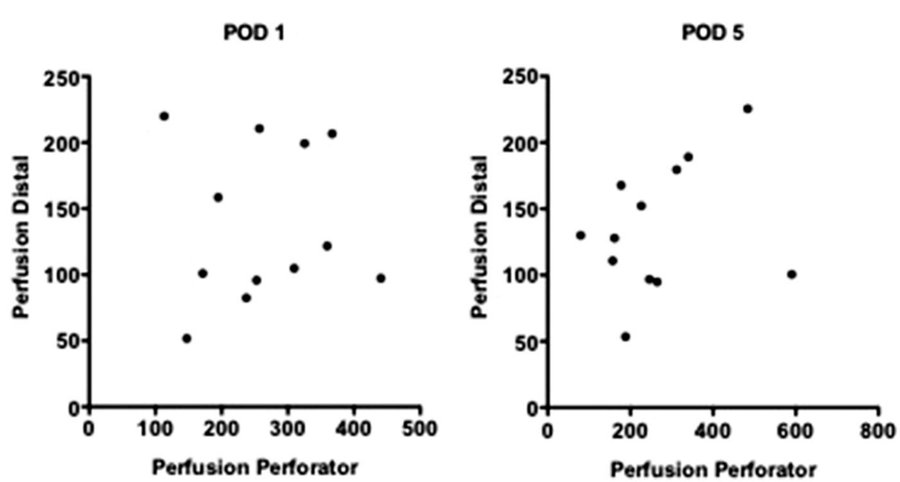

Figure 7. Correlation between Perforator zone and Distal zone perfusion at POD 1 (left) and POD 5 (right).

involving complex and large defects, particularly after cancer resection and severe trauma [16]. Along with advancements in microsurgical techniques, this has resulted in shorter operation times and higher success rates, with a success rate of over 95% being reported some centers [17]. Nevertheless, flap failure, which may be partial or complete, remains a challenging problem for both patients and surgeons, and has been directly linked to perfusion issues in the post-operative period. Thus, the ability to detect perfusion irregularities, particularly in the early post-operative period, may lead to interventions to increase flap survival prior to irreversible damage occurring. In this study, we characterized the early post-operative perfusion dynamics of the MSAP flap using a non-invasive technique, LDPI, in 12 patients.

The first significant finding was that the perforator zone of the flap had the highest relative perfusion at POD 1, 3 and 5 as compared to the distal zone, control zone and the whole flap. This is

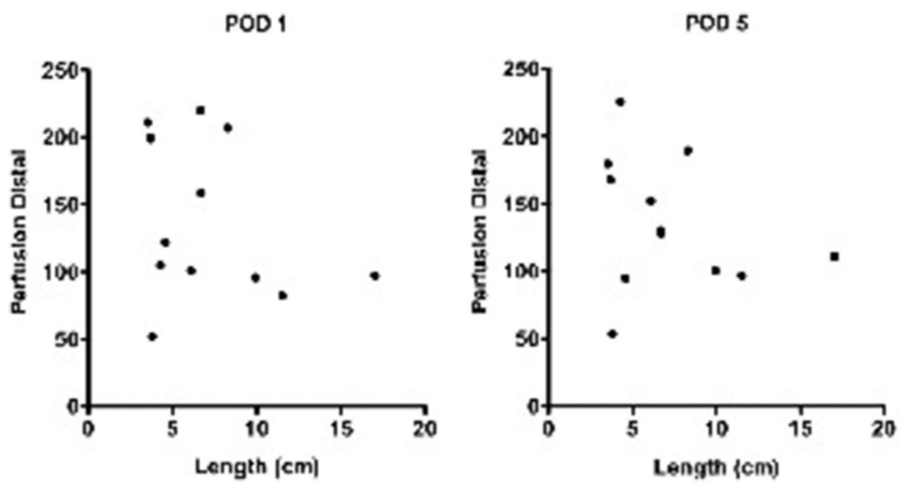

Figure 8. Correlation between Distal zone perfusion and flap length at POD 1 (left) and POD 5 (right).

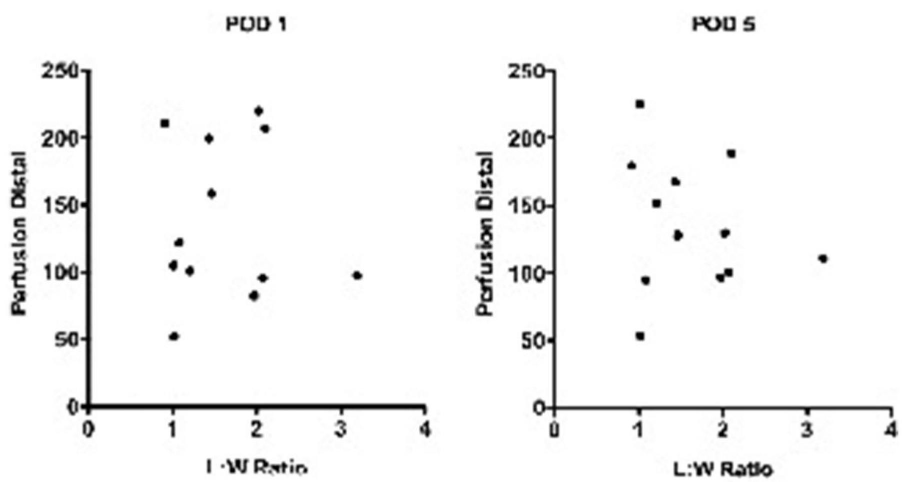

Figure 9. Correlation between Distal zone perfusion and flap length:width ratio at POD 1 (left) and POD 5 (right).

expected given that it is the site of main arterial inflow and venous drainage. However, less expected was that there was no significant change of perfusion within any zone measured over the five days. This suggests that once the anastomosis is performed and flap inset, the microcirculation remains consistent. Of course, it is plausible that a longer follow-up period may have demonstrated a temporal change in the perfusion dynamics not encountered before 5 days. However, given that most flap complications tend to occur within the first 48 h post-operatively, it is unlikely that a change in perfusion detected beyond 5 days would be clinically significant.

Of greater clinical significance is the finding that perforator zone perfusion correlates positively with whole flap perfusion across all five days. Whilst this suggests that LDPI monitoring of the perforator zone may act as a proxy for whole flap perfusion, the small nature of the MSAP flap limits this conclusion. Interestingly, perfusion at the perforator zone was not found to correlate with that of the distal zone. One plausible explanation for this is the involvement of interconnecting choke vessels, which may augment the blood flow between the perforator site, distal zone, and surrounding tissue [18]. Moreover, there was no significant correlation between distal zone perfusion and either flap length, or flap length:width ratio, which may otherwise have been expected.

There is a general lack of studies that assess the perfusion dynamics of free flaps following transplant from donor to recipient site. In this regard, our research group has made strides in studying various common perforator flaps and their post-operative perfusion. A noteworthy finding that appears common to several flaps, such as the anterolateral thigh (ALT) and MSAP flap, is relative *hyper-* perfusion of the area immediately surrounding the perforator zone, as well as of a ring of native tissue surrounding the margin of the flap (see Supplemental Figure 1). This trend appears from day one post-operatively, and continues through to the fifth post-operative day. In fact, this seems to support the angiosome and perforasome theory outlined by others [2,3]

To detect early perfusion changes, various invasive and non-invasive monitoring techniques have been introduced in free flap surgery with variable success rates [16,19–22]. Broadly, these measures fall into clinical assessment, biochemical measures (e.g. oxygen saturation, CO_2 monitoring, microdialysis, glucose, lactate etc.), or radiological techniques (e.g. ultrasound, multispectural imaging, fluorometry etc.). Currently, the standard evaluation of flap perfusion is based on regular clinical assessment of the flap colour, temperature, turgor and capillary refill time [23]. Although this approach is quick and non-expensive, its accuracy is dependent on the surgeons' experience and expertise, and is thus largely subjective. Additionally, the reliability of clinical assessment is further reduced in monitoring buried flaps, muscle flaps or flaps in patients with highly pigmented skin. An adjunct to clinical assessment is the use of the pinprick test, where a small puncture is made over the flap and the resulting flow of blood assessed to determine viability or perfusion issues as venous congestion. However, this is invasive and may lead to flap bruising [19].

Of the various methods for post-operative flap microvascular monitoring, only a handful have been shown in comparative studies to improve flap salvage rate [12]. Doppler ultrasonography is a fast and relatively easy procedure to monitor vascular flow, but is limited in its ability to distinguish between recipient vessels and flap perforator vessels [20,22]. Additionally, as vascular flow in a vessel is dependent on both the *velocity* of the blood flow and *cross-sectional area* of the vessel, and velocity is itself dependent on the angle of the probe to the axis of the vessel, this technique is limited by assessor technique. Implantable Doppler devices are a newer alternative which measure blood flow across a microvascular anastomosis, and in fact the bulk of studies relating to post-operative perfusion monitoring have compared this with clinical monitoring [12]. However, the Doppler probe is placed on either the artery or vein and consequently, concurrent arterial and venous occlusion can't be detected at the same time.

The use of LDPI, as in this study, is one of its core strengths given its non-invasive nature, reliability and reproducibility, and associated low false-positive and -negative rates [24]. Crucially, it was used in this study as it has been shown to detect flap compromise up to several hours before clinical signs are evident, which results in improved salvage rates [25]. The lack of any significant complications noted in our study may be attributable to the fact that MSAP flaps are typically small in size, with a reliable perfusion based on two angiosomes, which makes them an ideal candidate for extremity reconstruction. Whilst complications may have added value to our knowledge of how immediate post-operative perfusion dynamics detected *via* LDPI contribute to flap issues, in this clinical setting it would not have been feasible. Despite this, our study serves as a proof of concept paper for the use of LDPI in characterizing the early post-operative perfusion dynamics in free tissue transfer.

This study is limited by several factors, most notably the small patient sample sized used. Although not uncommon in microsurgical studies, this reflects the difficulty in recruiting large cohorts of patients over a short period of time in a field when technologies and techniques are constantly changing. Our study employed a practical approach in recruiting a patient population that closely mimics real-life practice in any major trauma reconstructive unit within a reasonable time period. In addition, all patients recruited had soft tissue defects within their extremities. This was chosen as these flaps are generally inset in a favourable location for scanning and monitoring. It is plausible that the perfusion dynamics vary with different anatomical locations (e.g. head and neck reconstruction) with the greater effect of gravity. Finally, although the methodology used is standardized and reproducible, this study was conducted in a center of excellence, with infrastructure support that may not be available elsewhere (e.g. a dedicated microsurgical intensive care unit).

Conclusion

This study utilized LDPI to assess the early post-operative perfusion changes in patients undergoing extremity reconstruction with MSAP flaps. We identified that the perforator zone has the highest perfusion, and this correlates with the overall flap perfusion, with obvious consequences for flap monitoring. However, the perfusion of any zone of the flap does not vary significantly with time, suggesting it may not act as an accurate predictor of flap survival. Although flap perfusion remains a poorly understood phenomena, our study serves as a methodological guide in employing LDPI to further our understanding. Future studies should look to evaluate a range of different perforator flaps of larger sizes (incorporating more angiosomes) for more prolonged periods of time, used in reconstructing various defects. However, the difficulty in performing such studies may prove limiting. AAt present, this study serves to further our understanding of MSAP flap physiology in reconstructive surgery.

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Disclosure statement

None of the authors have any commercial association or financial disclosures that might pose or create a conflict of interest with the information presented in this manuscript.

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