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Versatility and “flap efficiency” of pedicled perforator flaps in lower extremity reconstruction

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Posterior tibial artery perforator flap;
Defect

Summary *Background:* The use of pedicled perforator flaps provides an alternative to free tissue transfer for lower limb reconstruction. We use computer-aided image analysis to investigate the versatility of pedicled perforator flaps for the reconstruction of lower limb defects.

Patients and methods: Between April 2007 and April 2011, a case series of 61 patients with wounds of the lower extremity from knee to ankle were reconstructed with pedicled perforator flaps. We performed 16 pedicled reverse-flow anterolateral thigh (RF-ALT) flaps, 8 pedicled medial sural artery perforator (MSAP) flaps, 26 pedicled peroneal artery perforator (PAP) flaps, and 11 pedicled posterior tibial artery perforator (PTAP) flaps. Digital planimetry of defects covered was analyzed and the “efficiency” of each flap was calculated, which allowed the assessment of the merits of each flap in the management of lower limb defects.

Results: Flaps healed primarily in 82% of cases (50/61). Approximately 50% of the secondary donor sites required skin grafting. Complications requiring secondary surgery occurred in 18% (11/61) of the cases. Six required secondary skin grafting (10%). One RF-ALT flap was converted into a free flap, one PAP required arterial supercharging, and three pedicled RF-ALT flaps required venous supercharging. Image analysis showed that these pedicled perforator flaps could cover 75% of the surface area of the lower leg. The higher length of perforator allowed for greater “flap efficiency” and better versatility of tissue cover.

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Conclusion: Image analysis can be used as a modality to assess the versatility of individual flaps in the reconstruction of lower limb defects.

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Introduction

The technique of perforator dissection is a skill attributed to raising the modern free flap.^{1,2} This trend for intramuscular dissection of the perforator to provide extra pedicle length is gaining popularity as it allows for an increase in the versatility of local reconstructions.³ Flaps based on perforators aim to preserve the muscle function they pass through, and gain valuable pedicle length, hence maintaining the normal functional anatomy.^{4–6}

This technique is also valuable when recipient vessels are diseased or where microsurgical reconstruction is considered too “risky,” like in elderly patients or those who have significant comorbidities. It is a natural evolution of the locoregional flap reconstruction with the added refinement and confidence offered by visualization of the vascular anatomy.⁷ With flaps being close to the site of the defect, pedicled perforator flaps (PPFs) can potentially perform under regional block⁸ and reduce the need to transfer to specialized centers for postoperative microsurgical monitoring and care. In addition, they are less bulky, and are thought to have less associated risk than free flaps, as microsurgical anastomosis is not required.⁹ The use of PPFs also offer a comparable, “like for like” tissue type for reconstruction. However, perforator dissection is not universally practiced by all reconstructive surgeons.¹⁰

Our hypothesis was that using four different PPFs we could reliably reconstruct most defects from the knee to the ankle and we sought out to determine how well each flap covered a range of lower limb defects.

Using image analysis software, we evaluated the limits of use of lower limb PPFs based on four frequently used perforator flaps of the lower leg. The objective was to show the relative limitations of cover and “flap efficiency” of the different flaps in order to understand which situations best suit their use.

Patients and methods

A retrospective case cohort study was performed on all lower extremity PPFs performed between April 2007 and April 2011 at the Chang Gung Memorial Hospital using standardized perforator flap nomenclature described by Saint-Cyr.¹¹ Patients with consecutive lower limb injury or soft tissue defects who were felt to have low energy injuries and hence could be reconstructed by PPFs were included in this study, whereas those judged best managed by direct closure, skin graft, or free flap reconstruction were excluded. All cases were followed up until all wounds had healed. No cases were lost to follow up.

Data were collected on each flap group consisting of etiology, wound site and size, flap dimensions, advancement, rotation, donor site management, complications, and outcomes.

Calculation of “flap efficiency”

Multiple standardized photographs were taken, using a Canon DSLR camera, of the wound defect, the flap raised and flap at inset, from at least two different angles, with a single ruler scale and mapped onto a digital template using bony landmarks on a calibrated pixel mapping program on ImageJ Software.¹² Digital planimetry measurements were calculated after all calibrated images were taken ([Supplement Figure 1](#)). The precise area of defect, area of flap raised, area of flap inset, angle of rotation, and distance of flap advancement were measured using the measurement features in the software program. For the purposes of quantification, the lower limb surface area was defined as the level from the superior aspect of the patella to the forefoot excluding the toes and sole. The surface area was measured in cm² ($\pm$ standard error of mean).

The combined coverage of each flap according to the four types was mapped onto a surface area template and the percentage cover was calculated ([Supplement Figure 2](#)). Ratios were defined between size of defect to size of flap and size of flap to size of inset. Differences were sought between each perforator flap and analyzed for significance ($p < 0.05$) using analysis of variance (ANOVA) and post hoc Dunnett’s C test. The “flap efficiency” was calculated based on the degree of defect covered in relation to the flap size (surface area of defect requiring cover/surface area of flap raised $\times$ 100%) with the higher value indicating higher efficiency.¹³

Results

A total of 61 patients (18 females and 43 males) with lower limb wounds were reconstructed using PPFs. The mean age of the patients was 48 years (4–88 years). Fifty defects were caused by trauma, four by burn injury, four by tumor excision, two by infection, and one by venous ulceration. Overall, the flaps used in this series were able to cover 75% of the lower limb surface area ([Figure 1](#)).

Sixteen pedicled reverse-flow antero-lateral thigh (RF-ALT) flaps were raised with dimensions ranging from 12 $\times$ 6 to 27 $\times$ 12 cm ([Figure 2](#)). Donor site was closed primarily in 13 cases, with shoelace technique in two cases, and one by split thickness skin graft (STSG). Fascia lata for patellar tendon repair was included in three cases. Venous congestion was noted in eight cases, three of which were

Figure 1 Location of lower limb defects covered by pedicled perforator flaps in our series. Majority of areas have been covered except the area joining the proximal and middle third of the lower leg.

salvaged with venous supercharging with the long saphenous vein. Two that were not venous supercharged underwent partial flap necrosis and one had a minor wound infection. All other RF-ALT flaps survived without complication. Through surface mapping of the injuries sustained, the defects covered by this flap accounted for 26% surface area of the lower limb (Figure 1).

Eight pedicled medial sural artery perforator (MSAP) flaps were raised with dimensions ranging between 10×6 and 15×10 cm (Figure 3). Donor site was closed primarily in three cases, by shoelace technique in one case, and by STSG in four cases. All flaps healed without any complications (Table 1). The defects covered by this flap accounted for 15% surface area of the lower limb (Figure 1).

A total of 26 pedicled peroneal artery perforator (PAP) flaps were raised with dimensions ranging from 7.5×3 to 23×8 cm (Figure 4): 16 flaps were propeller, five were peninsular, two were advancement, two were proximally based island, and one was a distally based island flap. Donor site was closed primarily in five cases, by shoelace in one case, by skin grafting in 20 cases. Venous congestion occurred in five cases that had a propeller design, resulting in partial tip necrosis. These required secondary STSG in two while the rest healed by secondary intention. One case of arterial insufficiency was observed with advancement of a PAP flap that was salvaged by additional perforator supercharging with no subsequent complications (Table 1). The defects covered by this flap accounted for 22% surface area of the lower limb (Figure 1).

Eleven pedicled posterior tibial artery perforator (PTAP) flaps were raised with a surface area ranging from 12×3 to 24×5 cm (Figure 5): eight flaps were propeller, two were peninsular, and one was distally based island flap. The donor site was closed primarily in six cases and by STSG in

five cases. Seven flaps had uneventful healing course while four had distal tip necrosis that required STSG to heal (Table 1). The defects covered by this flap accounted for 19% surface area of the lower limb (Figure 1).

The average size of the defect requiring coverage was 68 (11) cm^2 for the RF-ALT flap, 39.5 (6.4) cm^2 for MSAP flap, 19 (3.4) cm^2 for the PAP flap, and 20 (6.7) cm^2 for the PTAP flap (Figure 6A).

Mean size of flap was 117 (18.7) cm^2 for the RF-ALT flap, 56.5 (6.8) cm^2 for MSAP flap, 65 (9.8) cm^2 for the PAP flap, and 68 (12.5) cm^2 for the PTAP flap. Inset saw a slight reduction in size of all flaps (Figure 6B and C).

The mean skin graft required for the donor site was 10.4 (10.4) cm^2 for the RF-ALT flap, 7 (3.4) cm^2 for MSAP flap, 22.5 (6.3) cm^2 for PAP flap, and 26 (15) cm^2 for PTAP flap (Figure 6D).

Advancement of the flaps was short for the PAP and PTAP managing on average 1.3 ($0-7.7$) and 2 cm ($0-3.7$), respectively. Advancement for the MSAP flap and RALT flap was significantly higher ($p > 0.05$) at 7.4 ($3.5-11.2$) and 19.6 cm ($9-29$), respectively (Figure 7A).

All flaps offered a good range of rotational freedom with the RF-ALT flap averaging 129° , MSAP averaging 80° , PAP averaging 94° , and PTAP averaging 62° (Figure 7B).

The flap size to flap cover ratio found most flaps maintained between 72% and 95% of their original size at inset (Figure 8A).

In terms of "flap efficiency," the least efficient was the PTAP (31.4%), followed by PAP (33.2%) then RALT flap (61%), and the most efficient was the MSAP flap (70%). The MSAP and RALT flaps were significantly more efficient than the other flaps ($p > 0.05$) (Figure 8B).

The flap characteristics and efficiency were summarized in Table 2.

Figure 2 A large lateral knee and proximal lower leg injury (A) reconstructed with a RF-ALT flap with “venous supercharging” to provide good lower limb coverage (B) and primary wound closure of the donor site (C).

Discussion

PPFs have revolutionized lower limb reconstruction as they liberate flap design from the constraints of width-to-length ratio, provide flexibility in design, and decrease donor site morbidity. The technique of perforator dissection is required to liberate the pedicle, and provide the flap with a higher range of freedom to cover the adjacent defect well.¹¹ In our series, PPFs have provided primary healing in 82% of our cases (Supplement Figure 3) with six cases requiring secondary skin grafting for unhealed areas and additional microsurgery being required to salvage five cases.

Hence, the perception that these forms of reconstruction have less associated risks and do not require microsurgical training is questionable. A recent systematic review has shown that the overall failure rate and complication rate were similar to that of free tissue transfer, whereas partial necrosis of PPFs was more prevalent at 7% compared with 2.7% in free flaps.¹⁴ It is important to realize the limitations of these flaps in the setting of lower limb trauma, they do not strictly represent the surgical panacea. In our practice, we make a balanced assessment based on the extent of trauma against bringing in free tissue on a patient-by-patient basis. Certainly, advantages include lesser surgical

Figure 3 A small prepatellar defect (A) reconstructed with pedicled MSAP flap (B) providing good skin match and cover (C).

time and like for like tissue. The main trunk of the supplying vessel is not disturbed and therefore flow to the distal limb is preserved during pedicled perforator flap transfers. But from our series, it is clear that microsurgical availability is important. Each flap can cover defects around the lower leg ranging from 15% to 26% of the surface area. The MSAP and ALT flaps provide cover around the knee, whereas the PAP and PTAP cover around the distal tibia and ankle. This leaves a watershed area around the proximal and middle third of the tibia that was not reconstructed by these four flaps. In our experience, free tissue transfer or local hemisoleus muscle flaps were preferred in this region.¹⁵

Perforator flaps can be raised at many anatomical sites where a decent perforator exists⁷ and can be identified

reliably by a handheld Doppler probe.¹⁶ Greater knowledge of the interlinking channels between perforators allow for larger more reliable flaps to be raised, as perfusion studies have shown, single perforators of the PTAP and PAP can perfuse flaps approximately 40% of the lower leg surface area each, between the ankle to knee joint.¹⁷ In certain circumstances where the perforators are not audible on Doppler, we have used the endoscope to directly visualize the perforators prior to raising the flap.¹⁸ We used our experience from perforator dissection in free flaps to provide a pedicle dissection as long as possible all the way to the source vessel to allow maximum pedicle freedom.

Most of these perforator flaps will require grafting of the secondary defect. In our series, 49% of cases required

Table 1 Summary of demographics, etiology, general flap type, management, and complications.

Flap type	Mean age	Etiology	Wound site	Flap dimensions	Subtypes	Donor site management	Secondary procedures	Complications	Outcomes
RF-ALT <i>n</i> = 16	35 ± 12 SD Range 16–50	12 trauma 2 burn 2 infection	12 knee 1 popliteal fossa 1 proximal tibia 2 knee stumps	12 × 6 to 27 × 12 cm	16 propeller	13 primary closure 2 shoelace 1 STSG	3 venous supercharging 1 conversion to free flap	2 partial flap necrosis 1 local infection 1 conversion to free flap	All healed
MSAP <i>n</i> = 8	44 ± 24 SD Range 15–73	6 trauma 2 tumor	3 tibia 4 proximal tibia 1 popliteal fossa	10 × 6 to 15 × 10 cm	8 propeller	4 STSG 1 shoelace 3 Primary closure	None	None	All healed
PAP <i>n</i> = 26	55 ± 21 SD Range 4–88	22 trauma 2 burn 2 tumor	2 medial ankle 7 lateral ankle 7 Achilles 2 heel 7 pretibial	7.5 × 3 to 20 × 8 cm	5 peninsular 16 propeller 2 advancement 3 island	16 STSG 4 FTSG 5 primary closure 1 shoelace	1 arterial supercharge 2 STSG	5 partial tip necrosis 1 arterial insufficiency - supercharged	All healed
PTAP <i>n</i> = 11	54 ± 16 SD Range 28–79	10 trauma 1 venous ulcer	4 medial ankle 3 midtibial 4 distal tibia	12 × 3 cm to 24 × 5 cm	8 propeller/ 2 peninsular/ 1 island	6 primary close 5 STSG	4 STSG	4 partial tip necrosis	All healed

grafting, which is higher than 30.3% reported in the literature.¹⁹ This is likely due to our high use of the PAP flap as a propeller flap, as the secondary defect in this area is not particularly pliable. Overall, our complication rate was 28%, with one flap conversion to free, which is similar to the reported literature.^{19,20} Four different PPFs were raised in this study, of which the PAP flap was the most commonly performed 26/61 (43%) and the RF-ALT flap was the second most common 16/61 (26%). In the literature, the PTAP flap is by far the more common flap performed, which accounts for 90% of all flaps used to reconstruct lower limb defects.²⁰ The bias of flap use may be a reflection of our center's vast experience with the fibula flap and antero-lateral thigh flap for head and neck reconstruction.^{21–23} Despite many injuries resulting in lateral leg and knee injuries, the perforators remained intact and a reliable source of perfusion for the flaps. In mapping all the defects onto the lower limb, we found that the four flaps could cover 75% of the lower limb total surface area from the superior patella to the forefoot (Figure 1).

The pedicled RF-ALT flap managed to provide coverage to both lateral knee and proximal tibia. Arterial insufficiency was not seen in our series but has been encountered in other studies.^{24,25} We found venous congestion frequent with the RF-ALT flap (50%), which we prospectively addressed by venous supercharging. The incidence of venous congestion has been reported as 6% in other series where the flaps were smaller.²⁴ On the basis of this, we advocated venous supercharging using the great saphenous vein if congestion occurs on table.²⁶ The need for microsurgery in such cases can be considered a major limitation of this flap.

The MSAP flap provided reliable soft tissue cover for medium-sized defects around the knee. A reported advantage of this flap is that it allows us to preserve the medial gastrocnemius muscle, which would commonly be sacrificed for coverage of defects around the knee. It is arguable how much function this preserves.²⁷ This flap has a long pedicle and high pliability, which make it very "efficient." However, the flap has a relatively small volume and the scar can be unsightly. Other options described include V–Y perforator flaps around the knee, based on fascial feeders in this region.²⁸ We found injuries around the knee and upper leg, such as muscular contusion or degloving to the calf from bumper injuries, would exclude the use of the MSAP flap as intramuscular dissection was hampered by a bruised field, even if the perforator was intact.

The PAP flap was the most used flap in this study. This flap was reliable in all its designs; however, the incidence of transient venous congestion in propeller flaps was high (19%). The constant septocutaneous perforators arising from the middle to distal third of the leg allowed for raising of flaps well suited for covering for distal half of the lower leg and ankle region.⁹ There was usually at least one reliable dominant perforator that could be used in keeping with reported anatomical studies³

We used propeller flaps most frequently. These flaps have high versatility to reach difficult-to-cover areas such as lateral malleolus, Achilles tendon, and dorsum of foot. The secondary defect usually requires skin grafting, which

Figure 4 A large lateral ankle fracture dislocation with skin loss (A) requiring a propellered pedicled PAP flap with skin grafting to secondary defect (B).

Table 2 Summary of flap characteristics and efficiency.

Pedicled flap type	Mean defect size cm ² (Range)	Mean flap size cm ² (Range)	Mean size of Inset cm ² (Range)	Mean area grafted cm ² (Range)	Mean rotation° (Range)	Mean advancement cm (Range)	Flap Efficiency % (Range)
RF-ALT	68 (21–143)	117 (49–256)	83 (35–134.5)	10.4 (0–125)	129 (49–180)	19.6 (9–29)	60.9 (24.8–100)
MSAP	39.5 (18.5–57.5)	56.5 (39.8–80.8)	50 (28–75.5)	7 (0–20)	80 (21–125)	7.4 (3.5–11.2)	69.9 (44.6–94)
PAP	19 (3.5–48)	65 (12–131)	42 (8–104)	22.5 (0–97)	94 (0–170)	1.3 (0–7.7)	33.2 (8–65)
PTAP	20 (5–42.5)	68 (33–100)	63 (33.5–99.5)	26 (0–55.5)	62 (0–167)	2 (0–3.7)	31.4 (8.5–49.7)

is a major limitation of this flap. In addition, the flap raised is usually much larger than the defect to provide cover largely due to its short pedicle, and hence less flap efficiency. Nonlinear finite element simulation calculated that a 1.0 mm diameter and 3.0 cm pedicle length is required to adequately provide 180° arc of rotation in propeller design.²⁹ Anatomical studies of the PAP flaps support these calculations claiming adequate rotation of vessels 0.8 mm in diameter with 3.7–5.4 mm pedicle length.³ The PAP flap based on the distal third of the lower leg is our favored

choice in traumatic injuries. The perforator is relatively robust and skin paddles in this area can be competent in this area even after previous fibular fractures.³⁰

PTAP flaps have the largest diameter perforators and have been extensively used in lower extremity reconstruction, often as propeller flaps.^{31,32} The PTAP was performed in 11 patients for medial-side leg defects. Thirty-six percent of these flaps had tip necrosis requiring secondary skin grafting or second flap cover. Schaverien et al.³¹ reported reliable reconstructions with this flap in a large

Figure 5 A medial ankle fracture dislocation with skin loss (A) reconstructed with a propellered pedicled PTAP flap (B), which allowed for direct closure of secondary defect.

series with a 8.5% complete flap failure rate, for which diabetes and occlusive artery disease appeared to influence, and Erdmann et al. reported 7.6% overall flap failure rate, with a further 10.6% of flaps suffering from tip necrosis.³³ Although Robotti et al. expressed high satisfaction with the PTAP flaps,³⁴ we found that the PTAP flap are less reliable than the PAP flap in the trauma setting.

In our experience, PTAP flaps provide thin and pliable soft tissue coverage of the medial malleolar region, the anterior shin and Achilles territories³⁵ and can provide a reliable alternative for lower leg and ankle defects in situations where PAP flaps may be compromised.

The limitations of this study include the heterogeneity of the defects being reconstructed and the relatively small flap numbers in some groups. There is also a degree of subjectivity in the selection of cases to be managed by PPFs as this decision is based on the surgeon's analysis of risk and suitability. The avoidance of microsurgical anastomosis is

one of the benefits of PPFs; however, the need to supercharge four cases in our study shows that on occasion microsurgery is needed to salvage. The RF ALT flap is especially prone and needs to be considered for supercharging routinely.

The techniques used to analyze the flap characteristics in this study is a first attempt at quantifying the relative "efficiency" of a flap and map the area that they can cover. A range of propriety wound assessment software exists and can be used to perform this task; however, Image J has been validated and is the choice of the scientific community because of its free access and extensive validation in research.³⁶ The value of this study would be to use this information to guide the clinical decision-making process of which flap to use for a given defect. Cumulative data acquisition using these measurements and location parameters, together with clinical data may be amenable to the development of algorithms that can predict which flaps

Figure 6 Comparison of mean reconstructive dimensions. A. Size of defect. B. Size of flap raised. C. Size of flap at inset. D. Donor skin graft area. (Error bars denote standard error).

Figure 7 Mean flap mobility. A. Flap advancement. B. Flap rotation (Error bars denote standard error).

are best used at which sites and provide an accurate risk assessment for any given reconstruction when all other patient factors are taken into account. Information gathered in this way aims to be part of “big data” acquisition, which is being used in many areas of health care to describe, predict, and model outcomes.³⁷ Three-dimensional wound measurement tools are under development, which would provide higher accuracy.³⁸ Our future work will aim to develop a more user-friendly application

Figure 8 Flap-to-cover ratio and flap efficiency (Error bars denote standard error).

specific for the lower limb to capture clinical data assessing the performance of all flaps.

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None of the authors has financial interest in any of the products, devices, or drugs mentioned in this manuscript.

Conflict of interest statement

None.

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Appendix A. Supplementary data

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