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ORIGINAL ARTICLE • HAND - MICROSURGERY

Propeller perforator flaps in forearm and hand reconstruction

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Abstract
After a long history in flaps' surgery, the perforator flaps became the most used flaps nowadays. From the beginning, their use as free flaps diminished substantially the donor site morbidity. In the attempt to not only diminish the donor site morbidity, but also to achieve more similar reconstructions, a new concept appeared 20 years ago: local perforator flaps. The local perforator flaps offer as main advantages the absence of microsurgical sutures ("microsurgical non-microvascular flaps"), same surgical field, the sparing of muscles and main vascular pedicles, and shorter hospitalization time. They can be used as V–Y advancement flaps, transposition flaps, propeller flaps, and keystone flaps (multiperforator flaps). The present study will refer to the use of local perforator flaps in forearm and hand reconstruction, and will point on the most important technical aspects of their harvesting, the main indications, advantages and disadvantages, and possible complications.

Keywords Forearm defects · Hand defects · Perforator flaps · Propeller perforator flaps

Introduction

Various methods have been used over the time for reconstruction of challenging tissue defects of the upper limb. But, if for the arm and proximal half of the forearm, the use of a free split thickness graft (FSTG) is generally adequate, the problem becomes more difficult for coverage of tissue defects in the distal forearm and hand. The superficial positioning of important anatomical structures (i.e. tendons, vessels, nerves, and bones) in these regions imposes in the large majority of cases the use of local, regional, or free flaps. A good cosmetic and functional result can be obtained by customizing the reconstructive procedure to each specific defect. The use of local or regional flaps seems to be the more rational choice because of their main advantages, i.e. short operation time, use of similar tissues for reconstruction, and no need of microsurgical sutures. One of the methods largely used in the past is represented by the reverse flow flaps based on one of the main arteries of the forearm, the most popular being the radial flap [1]. These flaps offer most of the advantages mentioned above, but have also the disadvantage of scarifying one of the main arteries of the forearm. That is why the new concept of perforator flaps was developed in the last 30 years, which allowed also the diminish of donor site morbidity by sparing the main vessels and muscles.

After a long evolution in flap surgery, which included random pattern flaps, muscle and musculocutaneous flaps, and fasciocutaneous flaps, Taylor and Palmer [2] reappraised the works of Manchot [3] and Salmon [4] regarding skin blood supply. They developed the angiosome concept, showing that this represents a block of tissue supplied by a same source artery and vein through branches for all tissues between skin and bone. Neighbouring angiosomes are linked to each other via "choke vessels".

A step forward was represented by the work of Saint-Cyr et al. [5], which focused on the perforator vessels and not the source vessel anymore. After conducting several anatomical studies, they defined the "perforasome" as the vascular territory of a single perforator and enunciated some clinically relevant principles:

1. The perforasomes are interconnected with each other by direct and indirect linking vessels. The direct linking vessels are macroscopic vessels, and they establish a direct "bridge" between branches of adjacent perfora-

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tors. The indirect linking vessels are microscopic vessels equivalent to the “choke vessels” described by Taylor and Palmer [2], and constitute the microscopic subdermal network.

2. The orientation of linking vessels dictates the design of a flap: axial in the extremities, and perpendicular to the midline in the trunk.
3. Perforators from a specific source have perforasomes that will be preferentially filled before filling perforasomes from adjacent source vessels

Moreover, Rubino et al. [6] have shown that by harvesting a flap based on a single perforator, the perfusion in this perforator will increase and contribute to the recruitment of adjacent perforasome territories. That can explain the large dimensions of some flaps.

As a result of this evolution, the era of perforator flaps started with the harvesting of the first flaps sparing the source artery and underlying muscle performed by Kroll and Rosenfield in 1988 [7] and Koshima and Soeda in 1989 [8], and the use of perforator flaps became increasingly more extensive. Free perforator flaps such as the anterolateral thigh flap, thoracodorsal artery perforator flaps, lateral arm perforator flap, inferior epigastric artery perforator flap, and biceps femoris perforator flap are used successfully for reconstruction of tissue defects in the upper limb.

The distant donor site, the difficulties in obtaining a similar reconstruction, and the technical high-demanding procedure are some of the factors that stimulated surgeons to find alternatives to free flaps. Nowadays, the use of local perforator flaps gained a big popularity, especially in the legs, due to some of their advantages: (1) replacing like with like, (2) donor site in the same area, (3) possible complete or partial donor site primary closure, (4) do not need microvascular sutures (microsurgical non-microvascular flaps), and (5) shorter operating time [9–14].

Chang et al. [15] described in 1988 a fasciocutaneous forearm reverse flap by sparing the radial artery (RA), but the real interest in using local perforator flaps appeared in 1994. Then, the use of local perforator flaps in forearm and hand reconstruction became increasingly extensive. They are mostly used as propeller flaps.

The term propeller flap was introduced by Hyakusoku et al. [16] in 1991 after performing an adipocutaneous flap blood supplied through a random subcutaneous pedicle and rotated through 90 degrees. In 2006, Hallock [17] used this term for the first time to define a perforator flap rotated through 180 degrees. The Advisory Panel of the First Tokyo Meeting on Perforator and Propeller Flaps defined in 2009 the term propeller perforator flap: a skin island with two paddles demarcated by the perforator vessel, which has to rotate through at least 90–180° [18].

Besides the advantages described above, there are also some possible drawbacks in using these flaps. The most important complications are represented by complete or partial flap loss due to venous problems, but the general complication rate is similar to that for free flaps. In an attempt to minimize the complication rate, the venous supercharging of a flap may be necessary. The careful planning and design of the flap, and of the length of the perforator is of maximum importance. Another important factor in diminishing the complication rate is the appreciation of the real dimensions of such a flap blood supplied through a single perforator pedicle. Initially, it was considered that the dimensions of a perforator flap are represented by the distance between two perforators, but later on Saint-Cyr et al. [5] demonstrated that a single perforator is hyper-perfused after cutting the other perforators, which increases its filling pressure and opens the linking vessels with adjacent territories (Fig. 1). The establishing of the safer dimensions of a flap before or during surgery can dramatically ameliorate the success rate. Hand-held Doppler, colour Doppler, duplex ultrasound, arteriography, magnetic resonance angiography, and

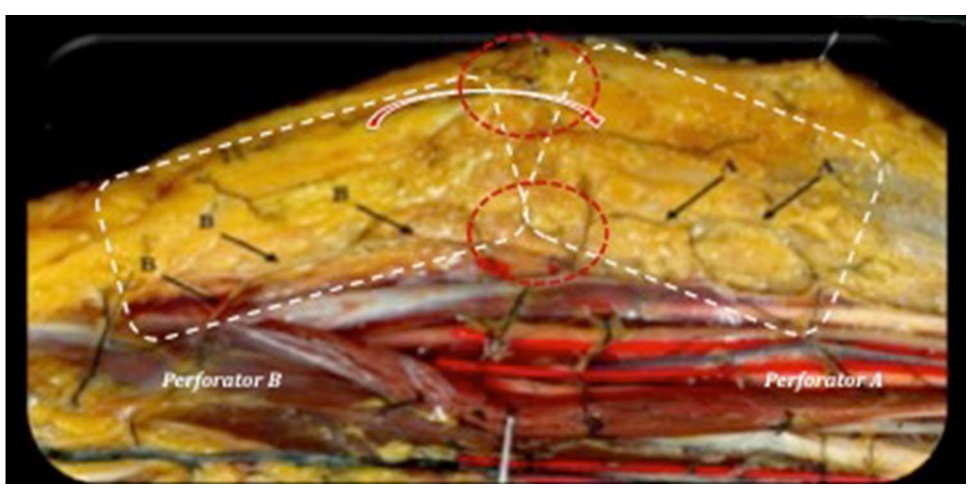

Fig. 1 Cadaver specimen after latex injection showing two perforators (**a** and **b**) with their territories (the pointed quadrangles); the red pointed circles represent the linking vessels between these two territories. If the perforator **a** is ligated, the pressure in the perforator B increases and opens the linking vessels (red arrow) with the adjacent territory of the perforator **a**

high-resolution computed tomography are methods routinely used to provide information about the perforator's distribution and/or calibre [12], but not regarding flap viability. New methods able to asses the flap perfusion during surgery, but not the dimensions of a flap, are represented by fluorescein [12, 19, 20] or indocyanine green near-infrared angiography [12, 20–23].

Due to the superficial location of the main axial source vessels in the distal forearm and hand, the identification of perforator vessels by Doppler examination before surgery is not very useful, because of possible false positive or negative results [10, 11]. In these conditions, it seems more reasonable to find the perforators during surgery by careful microsurgical dissection, and only after that to design the flap: that means to perform a freestyle propeller perforator flap (Fig. 2).

Anatomical considerations

The main axial arteries of the forearm, i.e. radial artery (RA), ulnar artery (UA), posterior interosseous artery (PIOA), and anterior interosseous artery (AIOA), contribute to the perfusion of specific areas of the skin, and constitute a rich anastomotic network with perforator branches providing blood supply to the skin, as well as the muscles, nerves, and bones. In the forearm, the main vessels follow the axis of the limb, and their perforators connect to each other by means of direct and indirect linking vessels [5]. Between the main arteries, there are also some transverse connections, which allow harvesting flaps with pedicles based proximally or distally on the perforators of those arteries [24].

The hand has also a very rich vascularization, based on perforators from the vascular arches realized mainly between the dorsal carpal arch (DCA) and the palmar arterial system [25, 26], but also on perforators of the common digital arteries (CDA) and proper digital arteries (PDA) [27].

Radial artery

The RA vascularizes the skin between the projection of the palmaris longus and the projection of the lateral edge of the extensor digitorum communis, excepting a small area over the lower part of the extensor pollicis brevis and abductor pollicis longus, which is supplied by the AIOA [28]. The territory of the RA extends proximally up to 5–8 cm distal to the epicondylar line of the elbow, but when the inferior cubital artery is present its territory can extend more proximally.

As demonstrated by Saint-Cyr et al. [29], the main perforators of the RA are distributed in two clusters of clinical relevance. The first one is located in the proximal third of the forearm, whereas the second one can be found in the distal fifth of the forearm (Fig. 3). These perforators arise between brachioradialis and pronator teres in the proximal third of the forearm and between brachioradialis and flexor carpi radialis in the distal two-thirds of the forearm. In the proximal part, the perforators are both muscular and septocutaneous, but in the distal part, they are only septocutaneous. One of the septocutaneous perforators in the proximal part is represented by the inferior cubital artery described by Lamberty and Cormack, which is the largest RA perforator and which allows the harvesting of a flap extending 10 cm distally from the apex of the antecubital fossa. Two large perforators can be also found within 2 cm proximal to the radial styloid. Other numerous but smaller perforators can be found between 2 and 7 cm above the radial styloid (external diameter of 0.3–0.5 mm). Moreover, one of the dorsal perforators given by the RA in the distal part, which is running under or over the brachioradialis tendon and penetrating through it and the abductor pollicis longus tendon, represents the vascular pedicle of a flap described by Koshima et al. [30].

Ulnar artery

The territory vascularized by the UA extends between the projection of the palmaris longus and the projection of the posterior subcutaneous border of the ulna.

The main group of perforators is found in the distal two-thirds of the forearm, the most important being located most frequently at about 8 cm proximal to the pisiform bone (Fig. 3). Yu et al. [31] have demonstrated that at least 2 or 3 perforators were consistently found in the forearm, on a line connecting the pisiform and the volar aspect of the epicondyle, or slightly ulnar to this line. Sun et al. demonstrated that the ulnar artery has two main clusters of perforators in the proximal one-third (7.73 cm $\pm$ 1.14 distal to the medial epicondyle) and distal one-fourth (4.57 cm $\pm$ 0.59 proximal to the pisiform bone) of the forearm. Both these clusters emerged from the space between the flexor digitorum superficialis and the flexor carpi ulnaris muscles. In a large series over 27 years, Mathy et al. [32] have found between 0 and 6 perforators in each forearm. At least, one perforator was found in 94% of the cases 3 cm within the midpoint from the line joining the pisiform bone and the medial epicondyle, and in 100% of the cases within 6 cm within the midpoint of the same line [32].

Posterior interosseous artery

The perfusion territory of the PIOA extends in a 5-cm wide strip from the lateral epicondyle to the head of the ulna.

There is an average of 5 large clinically relevant perforators arising from the PIOA and providing blood supply to the dorsal aspect of the forearm. These perforators tend to be more proximally located (Fig. 4). The perforators found in the lower third of the dorsal aspect of the forearm

Fig. 2 Technique of harvesting a freestyle propeller perforator flap: **a**. excision of a neglected posttraumatic skin necrosis; **b**. remaining defect after debridement; **c**. incision of only one edge of the potential flap; **d**. careful subfascial microsurgical dissection; **e**. identification and isolation of a perforator of the ulnar artery in the middle third of the forearm (no patent perforators in the distal third); **f**. it is better that the length of the perforator be of about 2 cm; **g**. the flap is completely incised and harvested; **h**. the harvested flap is rotated 180 degrees to cover the defect; **i**, **j**. post-operative result

arise from the AIOA rather than the PIOA [33, 34, 35]. Angrigiani et al. [33] and Hubmer et al. [34] have studied the anastomotic network between the AIOA and PIOA and have found that the distal third of the posterior forearm is vascularized by a recurrent dorsal branch of the AIOA. On the wrist level, the most distal perforators of the PIOA realize anastomoses with the AIOA, the dorsal carpal arch, and the UA [36].

Anterior interosseous artery

The perfusion territory of the AIOA is represented by the skin over the lower part of extensor pollicis brevis and abductor pollicis longus, and is realized through three perforating branches. The most important of these perforators emerges at the proximal border of the pronator quadratus

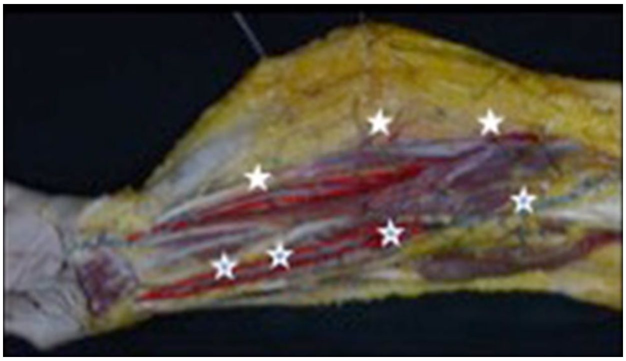

Fig. 3 Dissection in a fresh cadaver forearm, after latex injection. The picture shows the distribution of the perforators of RA (blue stars) and UA (white stars)

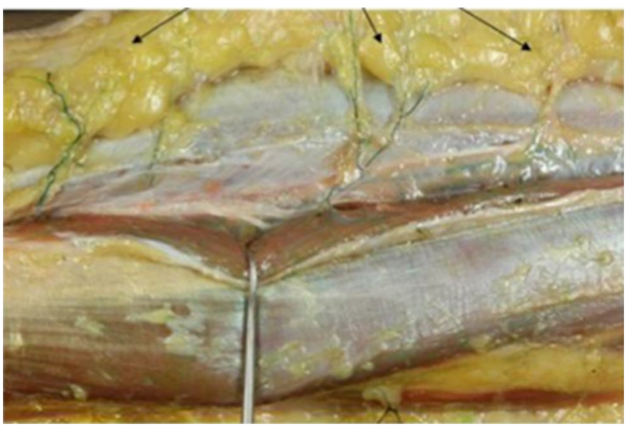

Fig. 4 Dissection in a fresh cadaver forearm, after latex injection. The main perforators of the PIOA can be viewed

muscle and supplies the skin over the distal two-thirds of the dorsal aspect of the forearm [37].

As shown by Yousif et al. [38], in the forearm the perforators emerging from these source arteries can travel either within or in close proximity to the deep fascia or through the subcutaneous tissue. It seems that the main source of the blood supply for the skin remains the subcutaneous arterial network. Schaverien and Saint-Cyr demonstrated this in a CT-angiography analysis on fresh cadavers. The authors investigated the perfusion patterns of both the subfascial and suprafascial forearm flaps with computed tomography. The 3D angiographies that were obtained showed no statistically relevant differences between the two techniques, indicating that a suprafascial dissection of the radial forearm flap does not compromise its blood supply [39].

The venous drainage of the skin is realized through one or two venae comitantes accompanying each perforator artery, which realize a very rich venous plexus draining both into the superficial and deep systems of veins.

Metacarpal arteries

The first dorsal metacarpal artery (DMA) and the DCA originate directly from the RA before it enters the palm. The second through fifth DMAs emerge subsequently from the DCA. The first, second and third DMAs are present in over 95% of the cases, whereas the fourth and fifth DMAs appear less consistent [40, 41]. The first through fifth DMAs have a mean diameter of 0.6, 0.8, 0.5, 0.4 and 0.2 mm, respectively. The DMAs provide four to eight perforators (0.1–0.3 mm in diameter) to the skin [41]. The DMAs run distal and pass through to the palmar arterial system at the metacarpal head level. A perforator originates from the junction between these vascular systems [26]. This perforator supplies the dorsal skin of the hand and is known as the perforator from the dorsal communicating branch of the common digital artery (CDA) or Quaba perforator. The blood flow is provided by the anterograde flow from the DMA or retrograde flow from the palmar artery system or dorsal digital arteries. The flaps based on this perforator can cover defects beyond the distal interphalangeal (DIP) joint. At the level of the proximal half of the first phalanx (P1) of the long fingers, corresponding to second to fourth web spaces, there are two important anastomoses: (1) at the union of the proximal with the middle third of the P1, between the DMA and the CDA; (2) at the middle of the P1, between the dorsal branch of the CDA and the dorsal branch of the PDA (Fig. 5). Because of the more distal situation of the pivot point, these flaps can reach also the distal phalanx, both dorsal and volar [42].

Fig. 5 Transparentation technique applied on fresh cadaver hand specimen with the arterial system injected with latex dorsal metacarpal arteries (DMA) and their anastomoses with the digital arteries can be seen

Flap design and harvesting technique

The preoperative planning of perforator flaps by using various imaging techniques and hand-held Doppler is not very useful in the forearm because of the superficial location of the main source arteries. It is also relatively difficult to do this in the hand [10, 11, 29]. Generally, the identification and isolation of the perforators in these regions is done intra-operatively in a freestyle manner through a careful dissection and consideration of the defect needs.

Only one edge of the potential flap is incised at the beginning. It is better to place this incision so that it is possible to be the limit of a second flap option, if a suitable perforator is not found. The incision can be either supra or subfascial. The dissection is performed under magnification, and all the significant perforators are preserved. In case of more adjacent perforators of similar calibre, they should be kept until the releasing of the tourniquet. The decision on which one of these perforators will be used as vascular pedicle of the flap is taken only after clamping them alternately. Only after choosing the right perforator, the definitive design of the flap is done. The long axis of the flap should be orientated in the long axis of the segment. The length of the flap from the pivot point, represented by the perforator, to the most distant point of the flap should exceed 1–2 cm in the forearm and 0.5–1 cm in the hand the distance between the perforator and the most distant edge of the defect. Similar, to the width of the defect is added 0.5–1 cm to allow the closure without tension. The perforator foramen should be enlarged, and all its muscular branches and fascial strands should be ligated or cauterized. It is considered that a length of 2 cm of the perforator ensures the optimal rotation of the flap. The incision around the flap is then completed (Fig. 2g), but it is better to rotate the flap only after releasing the tourniquet and observing the pulsation of the perforator, the bleeding from the flap edges, and the capillary refilling. In the absence of these signs, it is better to leave the flap in its original position for 10–15 min to allow the spasm to disappear. The direction of rotation should be carefully judged so to avoid kinking of the perforator. The donor site of the flap with a width up to 4 cm in the forearm and 2 cm in the dorsal aspect of the hand can be closed by direct suture. For larger donor sites, their dimensions can be diminished by advancement of the edges and the remaining defect should be covered with FSTG. One more possibility to diminish the donor site morbidity is to proceed to its preliminary expansion, which provides not only enough skin for the flap in regions with not sufficient resources, but also supplementary skin allowing its direct closure (Fig. 6).

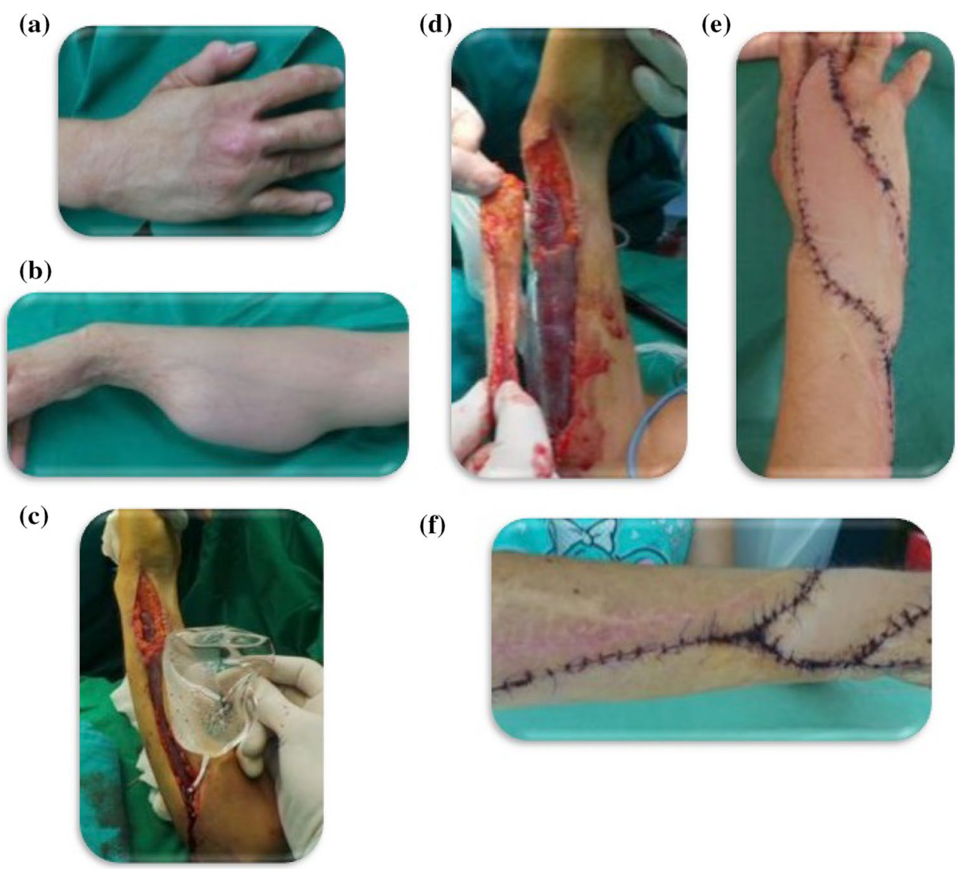

Fig. 6 Post-burn sequel of the dorsal aspect of the hand; **a**. preoperative aspect; **b**. the skin of the future flap is pre-expanded; **c**. after completing the progressive filling of the expander, this one is released; **d**. a perforator flap based on a distal perforator of the ulnar artery is harvested; **e**. the remaining defect after excision of the scar is covered with the rotated flap; **f**. enough skin remains to direct close the donor site because of the previous expansion

Advantages of propeller perforator flaps in the forearm and hand

The main advantages of propeller perforator flaps recommend them as a valuable option in the reconstruction armamentarium.

The surgical procedure is relatively easy and less time-consuming, which offers a lot of benefits to the elderly, multiple injured patients, or to those with a compromised general health status.

The reconstruction with propeller perforator flaps replaces like with like by using tissues of similar texture, thickness, pliability, and colour.

The use of propeller perforator flaps avoids the complexity, the multiple surgical sites, and the high costs associated with free flaps and microsurgery. Preserving the source artery and the underlying muscle, the propeller perforator flaps reduce drastically the donor site morbidity. For flaps with a width less than 4 cm in the forearm and 2 cm in the dorsal aspect of the hand, the donor site can be closed by direct suture, but even bigger defects can be partially directly sutured. The cosmetic appearance of the donor site can represent a significant drawback, but generally this one can be easily tolerated in very complex defects.

A potential disadvantage can be related to the location of the perforator within the zone of injury, but generally this fact does not interfere with the viability of the flaps.

Indications for propeller perforator flaps in the forearm and hand

The main indication for propeller perforator flaps is the coverage of small- to medium-size defects, but sometimes their dimensions could be larger. This happens in cases in which a perforator vessel cannot be found close to the defect. We harvested some larger flaps based on a single perforator, and the largest one in the forearm in our experience was an ulnar artery perforator flap of 26X7 cm (182sqcm). The explanation for survival of such big flaps can be found in the perforasome concept of Saint-Cyr et al. [5], according to which the hyper-perfusion in a perforator allows the capture of multiple adjacent perforasomes through direct and indirect linking vessels.

It is also considered that the propeller perforator flaps are a good indication for simple defects (Figs. 7, 8), but in our experience we used them also in very complex cases with good results. A patent perforator can be found by careful microsurgical dissection even in very complex traumas like amputations and partially degloving injuries (Figure 9).

The *radial artery propeller perforator flap (RAPPF)* is very thin and pliable, and can be harvested as chimeric flap including bone, muscle, and tendons, but can also be innervated and used as a sensate flap. Based on perforators from the proximal group, the flap is very useful for coverage of elbow region. The flaps based on distal perforators are very useful for coverage of hand defects. The RAPPF can also be used as an adipofascial perforator flap, very useful in the coverage of volar and dorsal hand wounds, treatment of recurrent de Quervain's tendonitis, flexor tendon sheath reconstruction, and wrist and median nerve padding. The use in such a way avoids the bulkiness observed after using a fasciocutaneous flap and ameliorates very much the donor site appearance. The donor site morbidity associated with the RAPPF when used as fasciocutaneous flap can sometimes surpass its advantages. Even if from functional point of view the morbidity can be minimized by harvesting the flap in a suprafascial plane, there still remain some drawbacks from the cosmetic point of view.

The *ulnar artery propeller perforator flap (UAPPF)* is also very thin and pliable, but is thinner and hairless if compared with the RAPPF. It can be also designed as a chimeric flap including bone, muscle, and tendon. It seems that because of all these facts, but also due to the lesser exposure of the tendons, the UAPPF leads to better

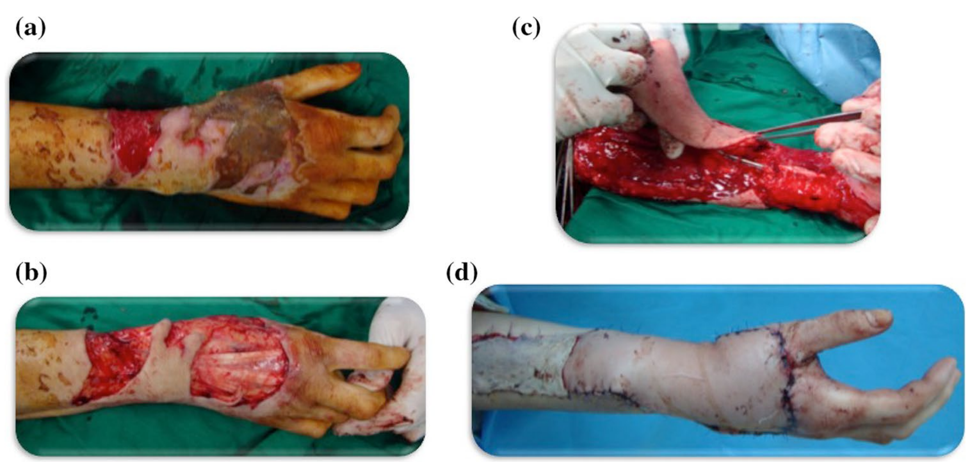

Fig. 7 Deep burn of the dorsal aspect of the hand and distal forearm; **a**. preoperative aspect; **b**. aspect after debridement; **c**. a propeller perforator flap based on a distal perforator of the radial artery is harvested; **d**. post-operative aspect

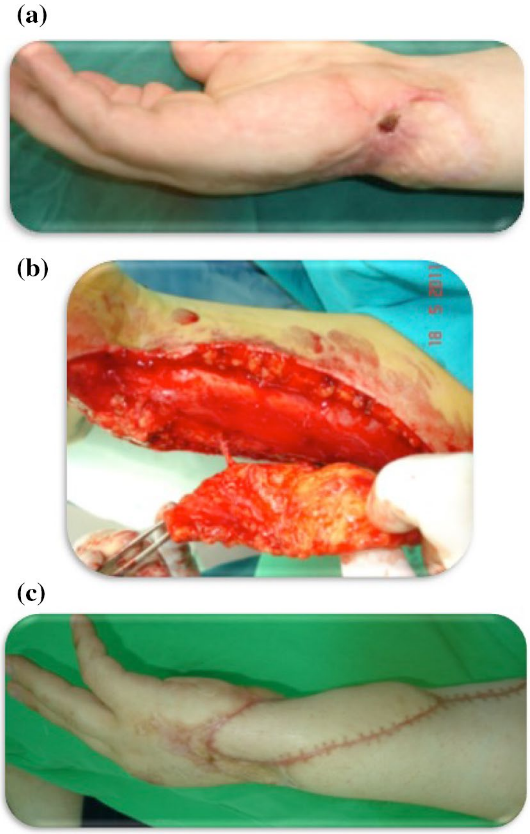

Fig 8 Fistulized osteitis of the ulnar styloid after electrical burn; **a**. preoperative aspect; **b**. a propeller perforator flap based on a distal perforator of the ulnar artery is harvested after debridement; **c**. post-operative aspect

functional and cosmetic outcomes [30]. The flap is very useful in the coverage of the dorsal aspect of the hand, of the hypothenar area and of the volar aspect of the wrist.

Both the *posterior interosseous artery propeller perforator flap (PIOAPPF)* and the *anterior interosseous artery propeller perforator flap (AIOAPPF)* have a structure very closed to the hand skin texture, which allows reconstructions of the dorsal hand with good outcomes, both functional and cosmetic. [34]. The PIOAPPF can be also harvested based on proximal perforators, finding its indication in coverage of elbow defects.

The *dorsal metacarpal propeller perforator flap* finds its indication in the coverage of small defects of the dorsal aspect of the hand and fingers beyond the distal interphalangeal joint, but also for more extensive defects of the fingers up to the distal phalanx, both volar and dorsal, when they are harvested based on commissural perforators—commissural propeller perforator flap.

Complications

The most common complication of propeller perforator flaps is represented by venous congestion of the tip or of the entire flap, and is due to the insufficient flow in the perforator pedicle. This happens either because of inadequate selection of the perforator, or due to its insufficient dissection and mobilization, especially around the vein. If venous congestion is observed intra-operatively, venous supercharging of the flap can be done by performing a microvascular venous anastomosis. In instances of signs of ischaemia, derotation of the flap to its original position can be attempted. In instances of vascular problems appearing after surgery, some flaps can be saved by removing the stitches, by doing small punctures or incisions and applying local heparinization, or by using leeches. If compared with free flaps, the loss of a propeller perforator flap involves generally only partial thickness of the flap. If a free flap is lost, everything is lost, while generally in a propeller perforator flap only the superficial part is lost. This means that the flap has done its job of covering the denuded anatomical elements, because after debridement the granulation of the wound is very fast and allows skin grafting.

To conclude, the presence of numerous perforator vessels supplying the forearm, hand, and fingers makes rational and reliable the harvesting of local perforator flaps in order to cover small- and medium-size defects. The functional and aesthetic outcome is more than acceptable, but their use needs further research especially regarding the real possible dimensions of this kind of flaps.

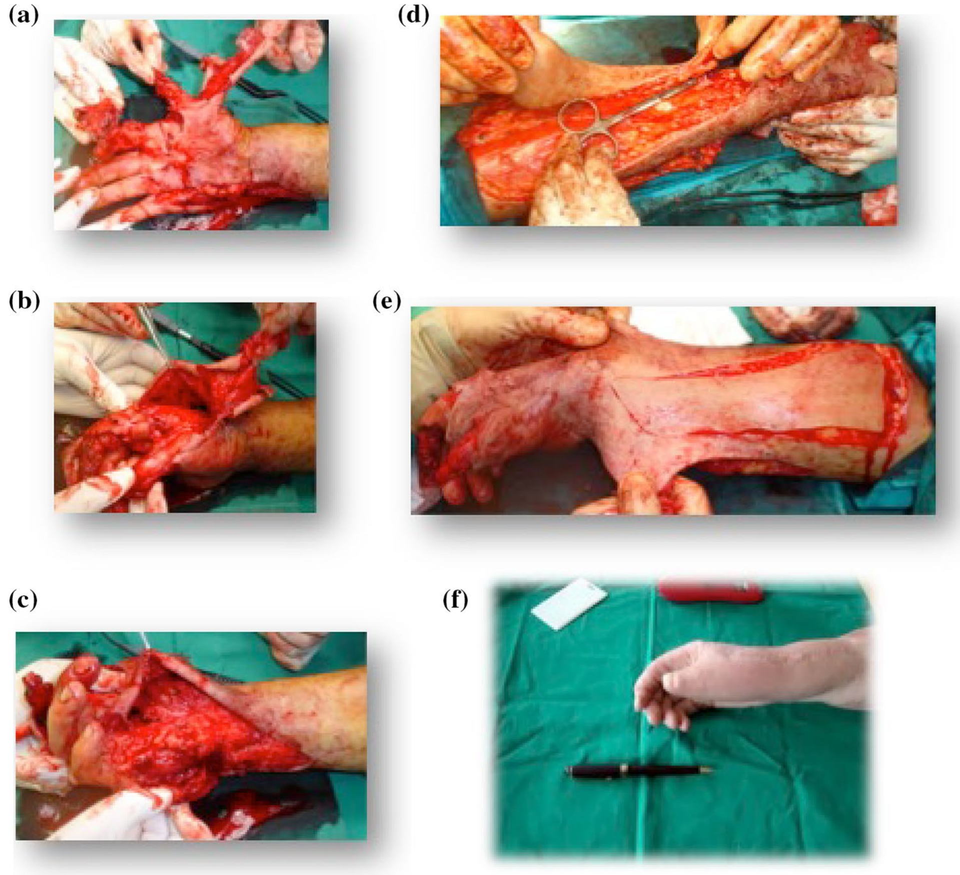

Fig. 9 Degloving crush injury of the hand and distal forearm; **a**, **b**, **c**. preoperative aspect showing the large degloving of the thumb, hand, and distal forearm; **d**. after very economic debridement, a perforator of the radial artery is found on the partially degloved forearm skin; **e**. a propeller perforator flap is designed based on this perforator and used to wrap around the thumb; **f**. post-operative aspect

Compliance with ethical standards

Conflict of interest All authors declare that they have no conflict of interest.

Ethical approval All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki Declaration and its later amendments or comparable ethical standards.

Informed consent Informed consent was obtained from all individual participants included in the study

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