# 5

# Classification of Flaps and Application of the Concept of Vascular Territories

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"*Πάντα Ρει*" (Greek "*everything flows*"). In other words "*the only constant is change*"

—Heraclitus

## Introduction

There have been numerous efforts over the past century to classify tissue transfer techniques that are used by plastic surgeons. To understand these efforts, we must appreciate the fact that these classifications have been promulgated to specifically characterize definite tissue units. These tissue units have commonly been referred to by plastic surgeons as "flaps." An "ideal" flap classification would ostensibly allow identification of any "flap" and place them unambiguously in one category or another. Such rigid regimentation of "flaps," while being semantically accurate, might lead to controversy and confusion in a practical world. Nevertheless, purists have made several attempts over the years to reach a conclusion only to make the classification scheme more convoluted. An ideal flap classification that is semantically accurate and at the same time pragmatic, unfortunately remains elusive. Interestingly, advances in flap classification have paralleled the explosive pace with which vascular basis of various "flaps" have been deciphered. Therefore, in this chapter the author attempts to summarize the classification systems that exist in the literature for every tissue type used as a "flap" and explain the vascular basis for such classification.

## What Is a "Flap"?

To classify anything, we must first appreciate what it represents. A "flap" may be defined as a tissue unit that, when transferred from its native location to a defect, does not rely on vascular ingrowth from the bed of the defect for its survival. In other words, the vascular network responsible for nourishing the tissue unit remains unchanged even after transfer of the flap. This is quite unlike a "graft" that relies on nourishment from the bed of the defect to ensure survival.[1] Interestingly, artificial tissue matrices such as Integra Bilayer Matrix Wound Dressing (Integra Lifesciences Corp. Plainsboro, Plainsboro Township, New Jersey) manufactured in a laboratory do not have native vascular networks either. Hence these matrices essentially behave as "grafts" when applied over a given defect. Tissue engineering has not reached a level where composite tissue matrices with a native vascular network can be manufactured.

## Criteria for Choosing "Flaps"

Flaps are required to reconstruct defects. It is useful to characterize any defect in terms of the anatomical and functional deficits that need reconstruction. A flap should ideally restitute both structure and function. However, it is not always possible to restore a defect back to its original state. Nevertheless, the essential functions should be restored. For example, following total glossectomy, the speech and swallowing functions need to be restored, but the taste sensations cannot be reconstructed with the available technology. In general, an anatomical defect may involve the skin (or mucosa), muscle, and/or bone in variable degrees. However, a single-tissue unit containing all the missing anatomical units may not be required to reconstruct every defect. As long as acceptable aesthetic and essential functional requirements are met, any "flap" may be used for reconstruction. Donor site morbidity is also an important consideration when one has the liberty of choosing one of two "flaps" with same tissue composition. If a flap is chosen such that a margin of the flap is situated adjacent to the defect, it is termed a "local" flap. All other flaps are termed "distant" flaps.

## Flap "Geometry"

Biogeometry has been defined by Tenta and Keyes as "*the integration and summation of the biologic and geometric factors that govern the logic involved in the process of efficient selection, siting, design, construction and transfer of a flap*."[2] A surgeon needs to have a systematic approach to flap geometry to have a successful reconstructive outcome. A flap has two basic parts: the "paddle" or the tissue unit that is being transferred and its "pedicle" consisting of the vascular and neural elements that are required for its nourishment. The reconstructive steps must be planned in a "reverse" order; that is, start with inset of a "bespoke pattern" of the proposed flap "paddle" in the defect, and then identify position of the pedicle, transfer of the pattern to the donor site, and finally mark the outline of the flap "paddle" on the donor site.[3]

## Design of Flaps

The tissue unit destined to be transferred can be circumferentially cut from the body and completely separated from its bed except at the entry point of its vascular pedicle and is termed an "island" flap (**Fig. 5.1a**). The term "island flap" (also called *biological* or *arterial flap*) based on only the dissected vascular pedicle was coined by the Dutch plastic surgeon Esser in the year 1917 for a cheek skin flap nourished by the facial or angular vessels.[4] However, if the flap is not completely cut from its surrounding tissues, it is termed a peninsular flap (from Latin words *paene* meaning "almost" and insula meaning "island") (**Fig. 5.1b**). The first flaps ever to be described were possibly "peninsular flaps" attached to the cheek and used to reconstruct the mutilated noses of subjects in the Indian subcontinent.[5]

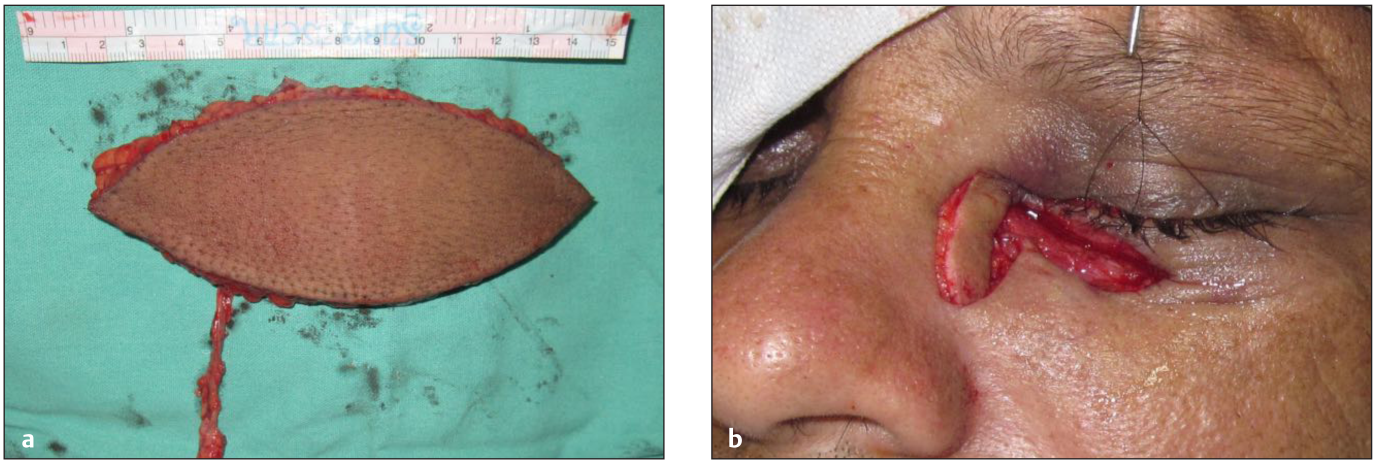



**Fig. 5.1** **(a)** Island skin flap with its vascular pedicle. **(b)** Peninsular skin flap with all sides incised except at the superior part, that is about to be transferred to a defect in the lower eyelid (published by permission from Adhish Associates Pvt. Limited, the copyright holders).

## "Movement" of a Flap

A mechanical force that is imparted to the pedicle of a flap determines the movement of the flap. When the force imparted to the pedicle is in the same linear axis as the direction of movement of the flap, it is termed an *advancement* flap. When the force imparted to the pedicle is nonrectilinear, the flap is termed a *pivot* flap. The word pivot is derived from the Spanish word *puya* meaning a point. Any tissue unit, which is transferred to a defect while being tethered at a point, is termed a pivot flap. This point around which the "flap" moves is termed the "pivot point" of the flap. The pivot is not a fixed or static point but can be dissected and moved to improve "reach" of the flap.

In certain situations, when the movement is not adequate to reach the defect, the static "pivot point" may be eliminated by making the flap "free". The transformation of the pivot to a free flap requires reestablishment of circulation by microvascular anastomoses of the artery and vein of the pedicle to recipient vessels near the defect. As a result, the pivot point of the "free" flap gets transported to the recipient vessels. The term "free flap" was first used by O'Brien in 1973 and has since been more popular than the term "microvascular surgery" that was introduced by Jacobson and Suarez in 1962. The unifying term "microvascular tissue transfer," despite being self-explanatory, never became popular.

Advancement flaps may be broadly classified into two subcategories: those flaps where the donor site can be closed primarily and those that need a skin graft for closure. Classic advancement flap is a rectangular-shaped peninsular flap that moves in the same direction as the long axis of the flap (**Fig. 5.2a–c**). The advancement achieved is due to mobilization and inherent elastic properties of the tissue.


**Fig. 5.2** **(a)** Large area of degloved scalp with devascularization of tip of the flap. **(b)** Following debridement of the devascularized tip and adequate mobilization of the flap. **(c)** Scar line after complete healing. Please note that the broad scar is due to deep dermal abrasions sustained during the original injury (published by permission from Adhish Associates Pvt. Limited, the copyright holders).

Triangular or "keystone"-shaped "island flaps" that are advanced in a linear fashion can have their resultant donor defects closed in a V-Y fashion (**Fig. 5.3a–c**). When a classic advancement flap design cannot completely close a defect, a horizontal incision is made parallel to the leading edge of the flap, the central part of the flap is elevated from its bed, and advanced in a direction perpendicular to the leading edge of the flap (akin to the movement of a bucket-handle). This is termed a "bipedicle flap," and it frequently will require a skin graft for closing the donor defect (**Fig. 5.4a–c**).

Pivot flaps may be classified into subtypes: rotation, transposition, interpolation, propeller, and turnover flaps, depending on the biogeometry of the flaps and the "*action imparted upon the pedicle during the surgical manoeuver used in the act of transfer*" of the flap.[2]

Rotation flap (derivative of Latin word *rota* that means "wheel") is one where "*the transfer maneuver imparts a radial arcing action upon the pedicle as the flap is rotated or wheeled into the recipient site, similar to the effect that occurs along the axis of a revolving door*."[2] The donor site defect is closed primarily by mobilizing the surrounding tissues (**Fig. 5.5a, b**). A suboptimally designed and executed rotation flap may require a skin graft for closing its donor site defect.

Transposition flap (derived from old French words *trans* meaning "across" and *poser* meaning "to place") is one where "*the transfer maneuver imparts an angular lateral (jackknife) action upon the pedicle. The angular (curvilinear) motion is similar to that occurring at the hinge when opening or closing a door or swinging a garden gate*." [2] The donor site is usually closed by use of a skin graft (**Fig. 5.6a, b**). However, Z-plasty,[6] slide-swing flap (as described by Schrudde and Petrovici)[7] and (**Fig. 5.7a–d**) rhombic flap designs (as described by Limberg[8] and Dufourmentel)[8] are examples of transposition flap designs where the donor site may be closed primarily.

Despite being described as distinct entities, rotation and transposition are movements that cannot be achieved independently for a given rotation/transposition flap design. Ahuja has definitively shown that advantages of both the movements can be incorporated by designing a flap that he terms the "local flap template."[9] The donor site is always closed primarily by mobilizing the surrounding tissues (**Fig. 5.8a, b**).

Interpolation flaps (derived from Latin words *inter* meaning "between" and *polare* meaning "to polish" or "alter the appearance") have predominantly transposition movement, but they are different from classic transposition design as the defect and flap donor site are separated by normal tissue. The "carrier segment" or pedicle of the interpolation flap (with a peninsular design) needs to be divided at a second stage or de-epithelialized and tunneled under normal tissue. Flaps raised from the central forehead for nasal reconstruction (**Fig. 5.9a–c**), "cross-digital" and "cross-leg" flaps are good examples of interpolation flaps. Island flaps which are interpolated to a distant defect, require their vascular pedicle to be passed under normal tissues.

A unique method of improving reach of a flap (with a fixed pivot point) is by "exteriorizing" the vascular pedicle of an island interpolation flap. For example, a skin paddle




Trap door flaps
or pull through flaps
are a type of interpolation flap

**Fig. 5.3** **(a)** Defect over radial aspect of left forearm. **(b)** Keystone design island advancement flap designed over ulnar skin. **(c)** Keystone design island advancement flap after 2 months (published by permission from Adhish Associates Pvt. Limited, the copyright holders).


**Fig. 5.4** **(a)** Defect over occipital scalp and nape of neck with exposed occipital bone **(b)** A bipedicle flap from the vertex of the scalp (with preserved superficial temporal vessels bilaterally) advanced inferiorly and skin graft applied to the donor site and nape of neck. **(c)** Transferred advancement flap over occiput (with exuberant hair growth) after 8 months with skin graft over vertex (alopecia). (Photos 5.4 (a) and (b) Courtesy Dr Pankaj Singodia and Dr Anirudh Mene).

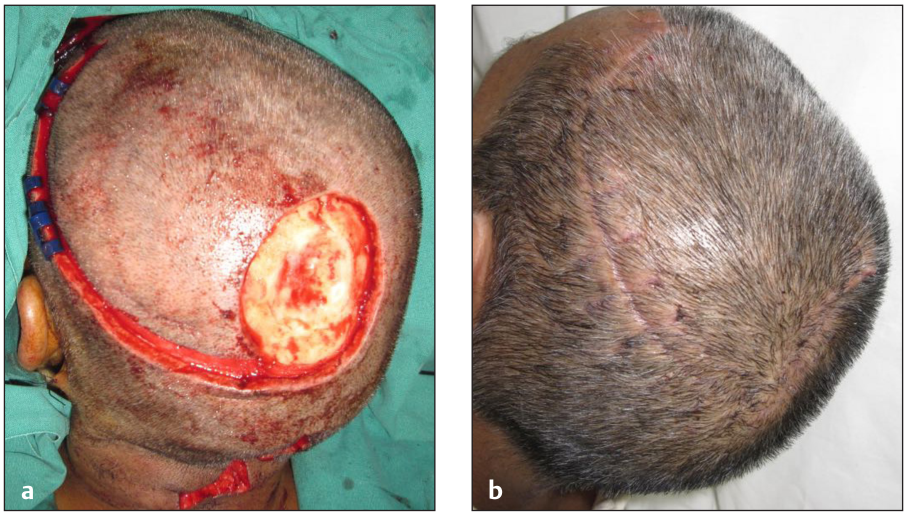



**Fig. 5.5** **(a)** Defect over occiput with a rotation flap elevated for cover. **(b)** Occipital defect covered with the rotation flap with primary closure of donor site (published by permission from Adhish Associates Pvt. Limited, the copyright holders).

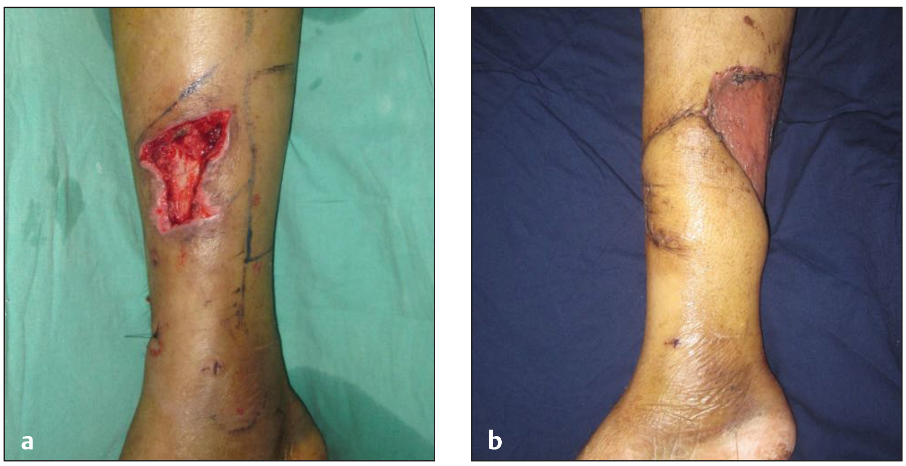



**Fig. 5.6** **(a)** Defect over right-side tibia. **(b)** Defect covered by transposing a skin flap with skin grafting of the donor site (published by permission from Adhish Associates Pvt. Limited, the copyright holders).

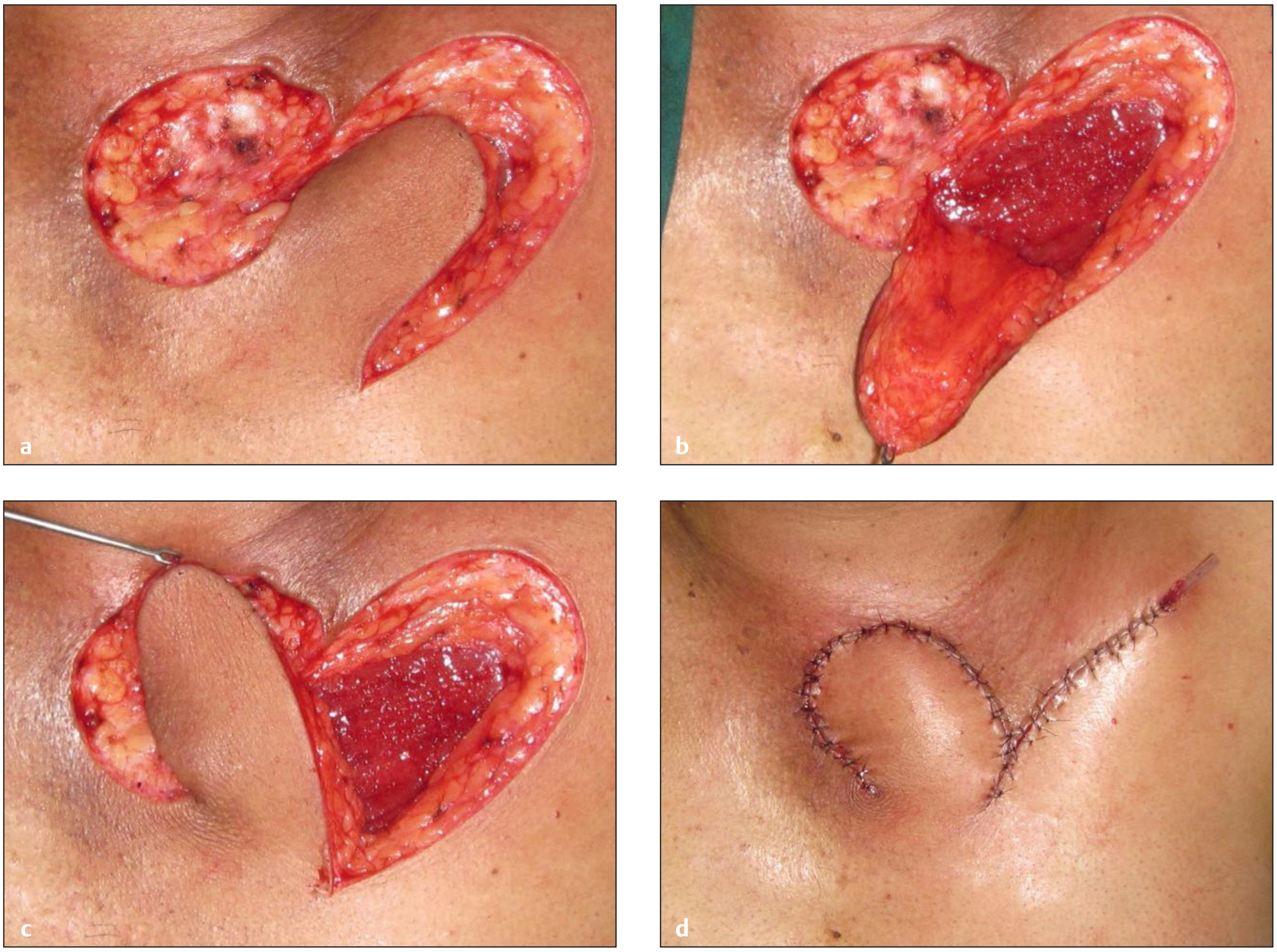



**Fig. 5.7** **(a)** Defect over chest wall with a transposition flap planned. **(b)** Transposition flap with an IMA perforator at its base. **(c)** Transposition movement of the flap into the defect. **(d)** Primary closure of the donor site by advancing local tissues (published by permission from Adhish Associates Pvt. Limited, the copyright holders).


**Fig. 5.8** **(a)** Defect over the scalp with a local flap template design marked out. **(b)** Defect covered by the flap moved by rotation and transposition (published by permission from Adhish Associates Pvt. Limited, the copyright holders).


**Fig. 5.9** **(a)** Defect over right nasal dorsum and cheek. **(b)** Defect covered using a forehead flap based on the supratrochlear vessels, which is interpolated into the nasal dorsal defect. Please note that the cheek defect has been resurfaced using a cheek advancement flap. **(c)** Final result after excision of the pedicle of the forehead flap (published by permission from Adhish Associates Pvt. Limited, the copyright holders).

raised from the proximal forearm can be made to reach the distal end of the fingertips by exteriorizing the vascular pedicle and extending the intervening joints (namely the wrist joint).[10] Govila devised an ingenious method of increasing the reach of the radial forearm flap by harvesting the flap and exteriorizing the pedicle (covered with a split-thickness skin graft) and then positioning the forearm such that the skin paddle could reach a facial defect.[11] As Govila's technique did not require a microvascular anastomosis, he termed it "extracorporeal tissue transfer." However, his technique required the same kind of prolonged immobilization of the upper limb, before division of the pedicle and final flap inset, as described by Gillies using his tubed flap on a "wrist carrier."[12] It is interesting to note that it was Halsted who first described the "waltzing" movement of a skin flap in 1896, which was popularized much later by Gillies[13] (**Fig. 5.10a–d**).

Propeller flap (derived from Latin words *pro* meaning "forward" and *pellere* meaning "to push) are defined per the Tokyo consensus conference as an "*island flap (resembling blades of an aircraft propeller) that reaches the recipient site through an axial rotation.*"[14] The nourishing pedicle of the island flap could be subcutaneous tissue (as described by Hyakusoku) or an isolated perforator (IP) (as described by Teo).[15] The donor site closure is aided by the 180-degree movement of one of the "propellers" of the flap (**Fig. 5.11a–e**). If primary closure of the donor site is not possible, a skin graft may be used.

Turnover flaps (or hinge flaps) are designed such that the flap is flipped over its base (or "bridge") in a fashion somewhat akin to turning the pages of a book. De-epithelialized skin flaps for resurfacing limb defects,[16] (**Fig. 5.12a**) turnover fascial flaps for reconstructing limb defects,[17] turnover nasal dorsal skin flaps for reconstructing the nasal lining, and turnover pectoralis major muscle (based on the Internal Mammary vessels alone) flaps for sternal defects are examples of hinge flaps.

It is important to note that advancement, rotation, transposition, and turnover are movements seen by default in local flaps. However, interpolation and propeller movements can be seen in both local and distant flaps. It is also interesting to note that flaps with identical vascular supply can be moved in two different ways to cover the same defect.[18] For example, a posterior tibial artery perforator flap may be interpolated to cover a defect in the leg (**Fig. 5.11**), whereas a de-epithelialized flap (nourished by the same perforator) may be used to cover a similar defect by a turnover maneuver (**Fig. 5.12b**). The de-epithelialized flap will require a split-thickness skin graft to cover the final raw area. The flap movement is chosen such that the "lie" of flap and its pedicle is comfortable and tensionless.

## Flap "Take"

Once a flap is inset into a defect, there is a gradual linkup of the tissue elements in recipient bed and the tissue elements of the flap. This is akin to "take" of a skin graft although the process is not identical. It is well documented that sensory recovery of a skin flap due to sprouting of nerve ends from the recipient bed provide protective sensibility even when a sensory neurorrhaphy is not performed.[19] Once a flap survives the transfer and settles, the vascular pedicle may be divided after a *sufficient* period of time has elapsed without compromising on flap viability.[20] The reason behind this phenomenon is vascular ingrowth from the recipient bed into the flap. The knowledge of these phenomena has been used by surgeons to devise ingenious techniques to transfer tissue.

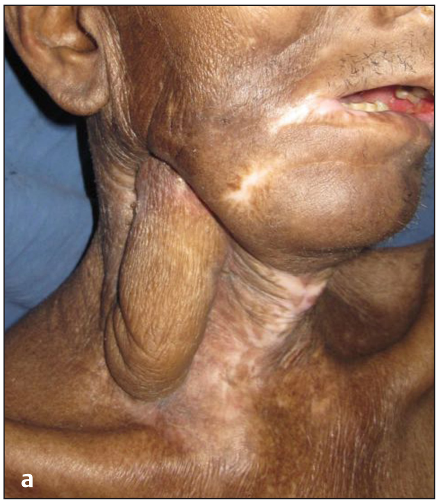


**Fig. 5.10** **(a)** Defect over submandibular region with dehiscence of previously inset of deltopectoral flap. **(b)** Distal end of deltopectoral flap inset into lower neck. **(c)** Proximal end of deltopectoral flap divided after 3 weeks and "waltzed" into the defect. **(d)** Final result after "waltzing" of deltopectoral flap (published by permission from Adhish Associates Pvt. Limited, the copyright holders).

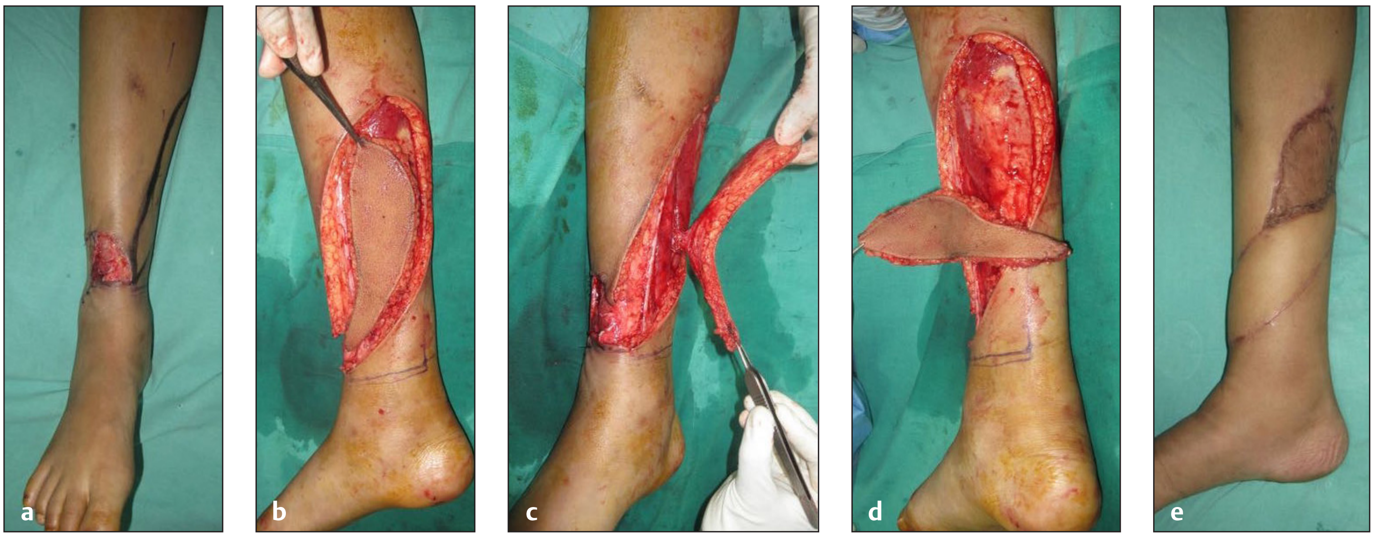


**Fig. 5.11** **(a)** Defect over lower leg with propeller perforator flap designed. **(b)** Propeller design flap elevated with dissected posterior tibial artery perforator. **(c)** Propeller flap elevated to show the dissected posterior tibial artery perforator. **(d)** Propeller flap being moved to the defect. **(e)** Final result 3 months after final inset with skin graft over the donor site (published by permission from Adhish Associates Pvt. Limited, the copyright holders).

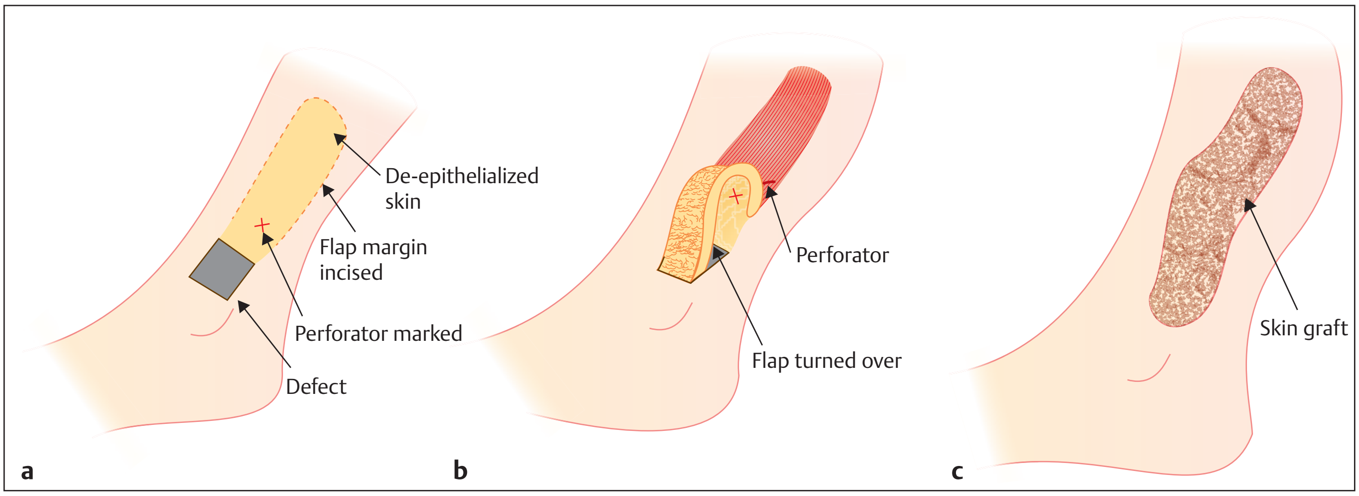



**Fig. 5.12** **(a)** Defect over lower leg similar to **Fig. 5.11a** with perforator localized preoperatively and the proposed flap marked. **(b)** De-epithelialized flap elevated and turned over into the defect. **(c)** Split-thickness skin graft over entire raw area.

## Techniques of Tissue Transfer Exploiting the Knowledge of Flap "Take"

### Flap "Training"

After inset of a peninsular interpolation flap, a *sufficient* period of time should elapse before the skin paddle "takes" on the defect and before the carrier segment can be excised. The period of time has been the subject of numerous experiments and is generally accepted to be around 2 weeks. However, to ensure flap survival, the "carrier segment" or pedicle may be subjected to intermittent mechanical compression leading to "hypoxia" of the skin paddle.[21] This maneuver encourages neo-vascularization from the wound bed and hence increases predictability of flap survival. This method of increasing flap survival is termed flap "training." Flap "training" can be accomplished by manual compression or by use of various custom-made compression devices.

### Crane Principle

Millard stated that "*a pedicle flap can be used as an engineering crane to lift and transport subcutaneous tissue from one area and deposit it in another. The pedicle can be returned later to its original bed…5 days later (or 12 days from the original implantation) there will be sufficient superficial capillary proliferation on the surface to nourish a split-thickness skin graft.*"[22] The underlying principle in this concept is to provide a layer of "subcutaneous tissue" over exposed bare bone, tendon, and other structures that would not "take" a skin graft, while minimizing donor site morbidity. The "crane principle" also allows tailoring of the thickness of "subcutaneous tissue" to be transferred by preserving an exact quanta of tissue on the wound bed, while *returning the remnant skin paddle and the carrier segment back to the donor site*. The second advantage mooted by Millard was that vascularization of the "subcutaneous tissue" (fat in case of abdominal flaps, galea in case of scalp flaps, etc.) was rapidly achieved within 1 week, resulting in optimal restitution of the patient.

### Flap "Recycling"

Recycling part of a flap, after the original has "taken" on the original wound or defect, for reconstructing a metachronous defect is termed flap recycling. Jeng and his coworkers have demonstrated both peninsular and island flaps (pivot and free flaps) harvested from previous flaps for reconstructing local and distant defects.[23] Recycling a flap is required to minimize donor site morbidity, especially when multiple donor sites have already been used or when the transferred flap(s) are too bulky and require contour correction. Recycling part of a flap (especially harvest of another perforator flap) is ill-advised in the presence of inflammation or following radiation of the original flap.

### Flap "Prelamination"

Modification of the "paddle" of a flap, by implanting autologous tissue or artificial matrices, before its transfer has been termed "prelamination."[24] It is important to note that for flap "prelamination," a defined vascular pedicle with its "vascular territory" is elevated after modifying its tissue constituents. Hence only when new components are added to an established flap territory, it is termed "prelamination." As such the nomenclature of the flap should not be changed. Flap prelamination is demonstrated when two epithelial surfaces are reconstructed with a skin flap with its undersurface lined by a skin graft.

### Venous Skin "Flaps"

The direction of blood flow as propounded by Harvey in his book *Exercitatio Anatomica de Motu Cordis et Sanguinis in Animalibus* (Latin for *An Anatomical Exercise on the Motion of the Heart and Blood in Living Beings*), published in 1628, has been accepted as artery to vein via capillaries. However, a skin flap can be made to survive, while maintaining continuity only via preserved subcutaneous vein(s) in the flap, by allowing vascular in-growth from the wound bed. Till vascular ingrowth into the skin graft occurs through the wound bed, the only conduit bringing it blood is a "vein." However, as per the definition of an artery, which is "*a conduit that takes blood away from the heart*," it is the author's contention that this "flap vein" should now probably be renamed a neo-artery. Thatte and Thatte classified skin flaps harvested with an "axial" vein into three categories[25] (**Fig. 5.13**):

- *Type I* or "unipedicled" venous "flaps" are those skin units with "*a single cephalad vein being the sole vascular conduit for perfusion and drainage*." In these "flaps," till vascular invasion from the wound bed occurs, only deoxygenated blood is responsible for survival. Hence a "venous composite graft" constituting skin and subcutaneous tissue is probably a more semantically correct term for type I venous "flaps." These "flaps" are as reliable as "large" composite grafts in a clinical setting.
- *Type II* or "bipedicled" venous "flaps" are those with "a vein entering (caudal end)" and then "leaving the flap (cephalad end)," the flow of blood being from caudal to cephalad. "The term "cephalad vein" would denote a vein toward the right heart, and the term "caudal vein" would denote the opposite, away from the heart." The initial survival of these flaps is also dependent on deoxygenated blood, and hence these flaps are as reliable as large "composite grafts" in a clinical setting.

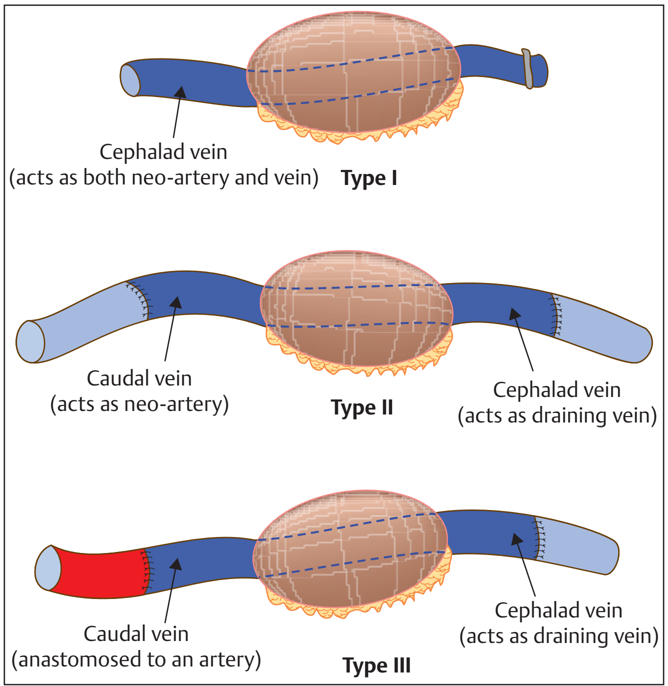



**Fig. 5.13** Venous skin "flaps" type I has a single conduit; type II has deoxygenated blood flowing from left to right; type III is basically an arteriovenous fistula.

- *Type III* "arteriovenous" flaps or "arterialized venous" flaps are those where the "caudal end vein" (neo-artery) is anastomosed to a recipient artery and the "cephalad end vein" is allowed to drain natively or into a recipient vein. These composite tissue elements have an initial period of venous congestion followed by "better" survival rates that types I and II "venous flaps." These flaps (especially when large) may have partial-thickness skin loss. The resultant arteriovenous fistula may need to be ligated at a second stage once the flap has settled. The use of small arterialized venous flaps (with sensory nerve coaptation) has been popularized for fingertip reconstruction in some centers. "Arterialized venous flaps" with recipient artery anastomosed to one of the cephalad veins (neo-artery) has also been described.

## Understanding Vascular Territories

As early as 1886 Carl Manchot, a Swiss-born medical student, a skilled artist and a scholar at the University of Strasbourg in France, was successful in mapping the pattern of vessels supplying the skin and predicted the existence of forty independent vascular territories that could be used as the basis for raising independent skin "flaps." His essay "Die Hautarterien des Menschlichen Körpers" ("The Cutaneous Arteries of the Human Body") published in 1889, however remained unknown to plastic surgeons till much later in the 20th century.

Skin flaps at the time would be raised on a trial and error basis as a piece of skin attached only at one point to the body. The term "flap" is derived from the Dutch word "flappe" that means something that hangs loosely from one side. The flap would generally include skin and subcutaneous fat and sometimes the underlying deep fascia as well. The plastic surgeons realized that in some areas of the body longer skin flaps would survive, whereas in other areas the tissue would undergo necrosis, especially distally. This resulted in various techniques to predict an improved flap survival. Staggering the elevation of the entire flap into stages and postponing its movement into a defect (described by Graefe in 1818); inclusion of an axial vascular network along the length of the flap (suggested by McGregor in 1972)[26]; or inclusion of underlying muscle or fascia with the skin (first described by Tansini in 1896)[27] were all recommended as means of improving flap survival. Wherever skin flaps were not reliable, using muscle bellies as flaps covered by a skin graft was suggested as a substitute by Ger in 1968.[28] As a result, rather than classifying flaps based on their vascular supply, plastic surgeons attempted to enumerate flaps based on their tissue composition or geometric design and mechanics of their movement.

Cormack and Lamberty in 1984 classified skin flaps based on the pattern and number of its nourishing vessels. A flap could either have multiple small feeders or a single large feeder vessel. Tolhurst in 1987 came out with an "atomic" classification scheme where he placed tissue composition of the flap as the "nucleus" and other defining features such as vascular basis, design, and movement as the "outer shell."[29] Both classification systems are, however, esoteric and not pragmatic.

An anatomical understanding of the vascular network was required to objectively classify flaps. Taylor and Palmer working out of their laboratory at the Royal Melbourne Hospital proposed a model for describing the vascular basis of flaps in the year 1987. Taylor's group was successful in identifying the three-dimensional (3D) units of tissue that were supplied by a named source vessel and named these units "angiosomes."[30] Angiosomes in turn were connected to each other via arterial anastomoses, some actual and others potential. Hence a flap could be raised provided the tissue unit was harvested along with its source vessel. The dimensions of a tissue unit could be increased by including the adjacent angiosome provided actual arterial and venous anastomoses existed between the angiosomes. Presence of anastomoses would enable elevation of both angiosomes based on a single-source vessel. However, the presence and location of these anastomoses could not be predicted at the time of flap elevation in a particular subject. Therefore, when a large flap was required, it was recommended that the blood supply from the adjacent source vessel to the adjacent angiosome be divided (before complete flap harvest), so that only one-source vessel would feed both the angiosomes. This was termed flap "delay." The same paradigm was extended to the 3D skin territory of a perforator and termed the "perforasome" by Saint-Cyr et al.[31] Taylor has termed the perforasome as a "perforator angiosome."[32]

The quanta of tissue that could be harvested based on a single-source vessel or perforator cannot not be predicted by either of the aforementioned theories. Hence a new paradigm was promulgated by the author and termed the "vasculosome" theory.[33] The author proposed elevating a tissue unit based on the longitudinal axial vessels present in every tissue unit. Each tissue unit, whether skin, muscle, or nerve, has an axial vasculature that needs to be identified. Once identified, any feeding vessel supplying this axis should be able to nourish the tissue unit that may encompass one or adjacent angiosomes. Taylor has termed the vasculosome as a "dynamic perforator angiosome" (**Fig. 5.14a, b**).

## Theories Explaining Vascular Basis of Flap Harvest

### McGregor and Morgan's Theory of Axial and Random Pattern Flaps (1973)

McGregor and Morgan defined "axial pattern flap" as "a single pedicled flap" that has an anatomically recognized arteriovenous system running along its long axis," and "random pattern flap" as "*a flap which lacks any significant bias in its vascular pattern.*"[34] They also went on to say that a "further evolutionary step" is to isolate the axial vessels supplying an island flap as in Littler's neurovascular island flap. At the time, although free digital transfers were being performed across the globe, free flap transfers as we know today was not described. Hence the terms "axial" and "random" patterns were restricted to skin pivot flaps.

McGregor suggested that there is an "overlap" of the so-called self-contained vascular territories as first suggested by Manchot. On the basis of dye injection studies (in cadavers) through various source vessels (e.g., the internal mammary artery [IMA] and the thoracoacromial artery), they concluded that the selective ligation of feeding vessels supplying an adjacent cutaneous territory may still result in skin survival because of "vascular pressure equilibrium" across "territorial boundaries." This is how they explained survival of the "random" extension of the "axial-pattern" deltopectoral flap across the deltopectoral groove.

### Behan and Wilson's Theory of Angiotomes (1973)

Behan et al, while injecting cadaver vessels with resin and contrast, established the presence of "linkage vessels" between adjacent "vascular territories."[35] The "axial-pattern"

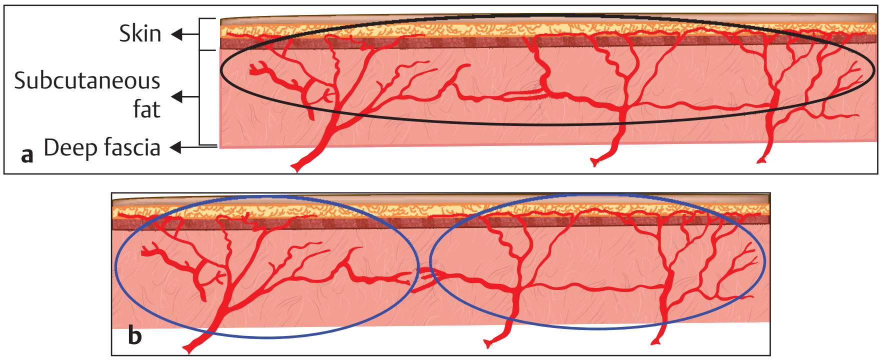



**Fig. 5.14** **(a)** A cutaneous vasculosome (black circle) being fed by three perforators; **(b)** Two cutaneous vasculosomes (blue circles) being fed by one and two perforators respectively.

vessel that supplied a "vascular territory" was termed the "prop" vessel. The quantum of tissue that could be harvested based on a single "prop" vessel could be extended to the adjacent "vascular territories" due to the presence of "linkage vessels" connecting them. This entire tissue unit with "linked" axial-pattern vessels was termed an "angiotome" by Behan. Behan could demonstrate these cutaneous angiotomes in the forehead and the deltopectoral region of chest of cadavers. He also emphasized the importance of preserving the deep fascia on the underside of these skin flaps. Behan has demonstrated that if a skin flap (with preserved deep fascia) unit was islanded with only the underlying (undissected) perforators (which Behan termed "support vessels") kept intact, the entire flap (or angiotome) would survive.[36]

## Taylor's Theory of Angiosomes (1987)

Taylor injected cadaver vessels and identified 3D territories of tissue supplied by a single-source vessel.[30] They also defined the "boundary" of each of these anatomical vascular territories, which they termed "angiosomes," by the presence of "choke" vessels. Each angiosome is "a composite block of tissue that span between the skin and the bone" and is supplied by a single-source artery. These "choke" vessels as described by Taylor form the watershed between two adjacent angiosomes and are present in every conceivable tissue plane, for example the subcutaneous tissue, muscle, bone, etc.[37] There are some vessels between two adjacent angiosomes that Taylor termed as true anastomosis, for example confluence of posterior tibial and dorsalis pedis arteries. Taylor and his colleagues also identified a "chain-linked system of arteries" in the subcutaneous tissue that accompany subcutaneous nerves, especially in the extremities.[38]

Taylor and his colleagues also performed animal experiments to predict flap survival. Their experiments on sequential ligation of cutaneous perforators to increase the dimensions of a skin flap in dogs led to the concept of an "anatomical" vascular territory (anatomical angiosome) and a "physiologic" vascular territory (physiologic angiosome).[39] The "capture" of tissue from the adjacent angiosome could be achieved by sequentially ligating the supply from the adjacent source vessel providing enough time for the "choke vessels" to enlarge and mitigate ischemia of the "captured" tissue.

The drawback of Taylor's model of vascular territories is that it relies on an anatomically rigid concept that cannot predict the exact quantum and dimensions of tissue that may be harvested based on a single perforator vessel in a clinical situation.

## Cormack and Lamberty's Theory of Dynamic and Potential Vascular Territories (1994)

Cormack and Lamberty in their book *The Arterial Anatomy of Skin Flaps* introduced the terms "dynamic" and "potential" vascular territories to explain the phenomena of "*random extensions of axial-pattern flaps*" and flap "delay," respectively.[40]

The dynamic territory is therefore the quantum of tissue that survives (or is successfully "captured") on a particular feeding vessel, after elevation of a flap whose dimensions are clearly beyond the anatomical territory of the said feeding vessel. The potential territory, on the other hand, is the "maximum" quantum of tissue that can survive, after elevation of a flap whose extent is even beyond the adjacent angiosome. A "delayed" flap and an expanded flap are good examples of harvest of "potential territories."

## Saint-Cyr's Theory of Perforasomes (2009)

Saint-Cyr and his colleagues injected isolated perforator arteries in cadavers and observed dynamic movement of contrast through the tissues using computed tomography.[31] "*Flaps were scanned with contrast medium injected simultaneously during a predetermined time interval to appreciate the characteristics and distribution of vascular perfusion.*" Based on their observations, they laid out certain principles:

- *First* principle: "*Each perforasome is linked with adjacent perforasomes by means of two main mechanisms that include both direct and indirect linking vessels.*"
- *Second* principle: "*Flap design and skin paddle orientation should be based on the direction of the linking vessels, which is axial in the extremities and perpendicular to the midline in the trunk.*"
- *Third* principle: "*Preferential filling of perforasomes occurs within perforators of the same source artery first, followed by perforators of other adjacent source arteries.*"
- *Fourth* principle: "*Mass vascularity of a perforator found adjacent to an articulation is directed away from that same articulation whereas perforators found at a midpoint between two articulations or at the midpoint in the trunk have a multidirectional flow distribution.*"

## Author's Theory of Vasculosomes (2015)

Limitations of the existing theories explaining the vascular basis of tissue harvest led the author to postulate the "vasculosome theory."[33] Based on a review of the existing literature, experimental data, cadaver imaging studies, and the author's clinical studies, a new theory that can predict complete flap survival was mooted. The author identified existing vascular axes in a particular plane in any tissue element spanning several so-called anatomical angiosomes. These vascular axes are fed by nourishing cutaneous perforators, muscular branches, and other nourishing vessels to the tissue elements. The directionality of such axes is not constant and may change with sequential ligation of "feeder" vessels. The author postulates that if the entire axis is preserved in the tissue element being harvested, the entire tissue "flap" will survive. The author has proposed certain principles of the "vasculosome[41]:

- *First* principle: The length of flap that could successfully be harvested depends on the inclusion of the putative "vascular axis" in the suprafascial plane. This was confirmed by satisfactory retrograde bleeding from the divided perforators[42] (**Fig. 5.15**).
- *Second* principle: Although suprafascial perforator directionality may suggest the direction of the vascular axis, the determination of this axis is a dynamic phenomenon and the "preferred vascular axis" changes with differential perforator clamping during flap elevation.[38]
- *Third* principle: Flap "delay" induces the formation of a neo-vasculosome.
- *Fourth* principle: The muscle "vasculosome" has one or more "vascular axes" in the muscle. A single feeding vessel supplying any part of the muscle can nourish the entire muscle provided a "vascular axis" exists. Even so-called traditional "minor" pedicles can perfuse an island-muscle flap based on a single perforator, provided they feed the "vascular axis."[43]

# Effect of Manipulation of Vascular Pedicle on Flap Nomenclature

## Flap Nomenclature

Flap nomenclature appears esoteric but is very important for accurate documentation. To have comparative studies internationally, it is important to have a universally accepted system for naming and identifying flaps. In 1977 Converse said "*the anatomical vascular basis of the flap provides the most accurate approach for classification.*"[44] The vascular anatomy provides the most pragmatic basis for classification of flaps.

To explain the difficulties in classifying flaps, certain examples will be illustrated. For example, Bakamjian's deltopectoral flap includes skin, subcutaneous fat, and the pectoral fascia, and is based on the internal mammary perforator vessels (which are neither identified nor isolated). This flap can be termed a "fasciocutaneous" flap as it includes the skin and the fascia. On the contrary, as it is based on the vessels perforating the intercostal muscles, it could also be termed a "muscle perforator" flap. However, the IMA perforator flap that has the same cutaneous paddle as the deltopectoral flap has individual IMA perforators dissected through the muscle (**Table 5.1**). Effectively one would have to name every flap differently to identify those harvested using a different technique. Such a scheme cannot be used as an effective classification system. However, the vascular basis of the flap would remain constant no matter how the flap is dissected or geometrically moved.

## Vascular Pedicle of a "Flap"

Vascular pedicle of a "flap" is defined as the artery and vein supplying the base of a flap. A flap is designed keeping the location of the pedicle at the center or at an eccentric location, depending on the defect to be reconstructed and the length of the vascular pedicle.

Mathes and Nahai (1997) classified vascular pedicles into three categories: major (dominant), minor, and secondary segmental pedicles.[45] Major or dominant pedicle is one that "*will support the entire area of flap design.*" Smaller pedicles that "*cannot support the area of flap design and the entire flap territory by themselves*" are termed "minor pedicles." These minor pedicles can be ligated with impunity when a flap is raised preserving a major pedicle. "*A series of minor pedicles that will preserve flap circulation and allow safe flap elevation after division of a dominant pedicle*" are termed "secondary segmental pedicles." The difference between minor and secondary segmental pedicles is neither anatomical nor physiological; rather it depends on how many of these "minor" pedicles are included in the flap. Multiple "minor" pedicles can support a quantum of tissue that a single minor pedicle cannot. This phenomenon can be explained using

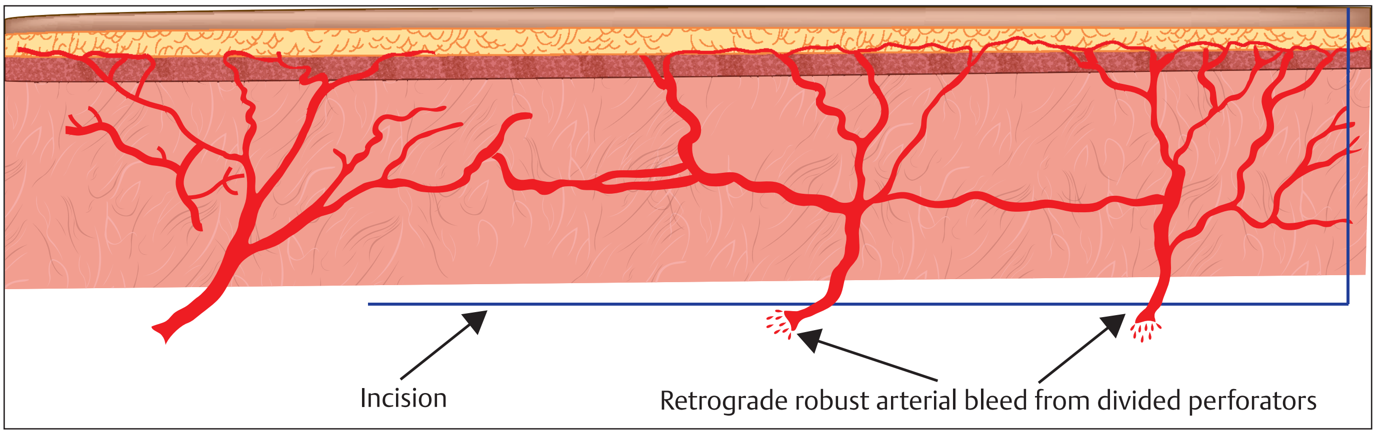



**Fig. 5.15** Physiologic explanation of how a flap raised with the axis preserved leads to complete survival.

**Table 5.1** Vascular elements and flap nomenclature

| | |
|---|---|
| Skin flap | A flap that includes epidermis, dermis, subcutaneous fat, and its vascular pedicle. |
| Vascular pedicle | Artery and vein supplying the base of a flap. A flap is designed keeping the location of the pedicle at the center or eccentric, depending on the defect to be reconstructed and the length of the vascular pedicle. |
| Microcirculation | The terminal part of the vascular tree responsible for exchange of gasses, metabolites, and nutrients at the cellular level. Consists of arterioles, venules, and capillaries. The vascular channels with a diameter of ≤300 μm constitute the microcirculation. |
| Cutaneous microcirculation | The cutaneous microcirculation can be identified in the dermis. The epidermis has no microcirculation and gets its nutrition by diffusion from the dermal microcirculation. |
| Dermal vascular plexus | The vascular plexus located in the superficial papillae of the papillary dermis. |
| Subdermal vascular plexus | The vascular plexus located between the reticular dermis and the subcutaneous fat, which is fed by the perforator vessels. |
| Suprafascial vascular plexus | The vascular plexus located superficial to the deep fascia (wherever discernible) or superficial to the epimysium over muscles (wherever the deep fascia is not discernible). |
| Source vessel | Any vessel that supplies a 3D unit of tissue that may include skin, subcutaneous fat, fascia, muscle, bone, nerves, and/or lymphatics is termed a *source vessel*. |
| Perforator vessel | The vessels (arising from a source vessel) that either pass through or in between "deep tissues" (most commonly muscle) are termed *perforators*. These vessels branch out in the subcutaneous fat and dermis to form the suprafascial, subdermal, and dermal vascular plexus. |
| Deep fascia | Layer of connective tissue that invests the muscles. The deep fascia sends out intermuscular fascial septa. The deep fascia is a distinct anatomical structure in the limbs but is barely discernible in the torso. |
| Fasciocutaneous flap | A flap that retains the deep fascia on the undersurface of a skin flap. The reason for retaining the fascia is to protect the underlying vascular plexus. |
| Adipofascial flap | A flap that consists of only the deep subcutaneous fat and deep fascia and hence retains the suprafascial vascular plexus. The overlying skin along with the subdermal vascular plexus is retained at the donor site. |
| Skin paddle | The island of skin that forms the cutaneous part of the flap. The radial forearm flap consists of a skin flap and its vascular pedicle, whereas a chimeric flap may contain one or more skin paddles, a muscle segment, and/or a bone segment. |

the author's "vasculosome" theory that states that pedicles (both major and secondary segmental) feeding the "vascular axis" will be able to support an entire flap territory, whereas those pedicles (minor) not connected to the "vascular axis" will not.[41]

## Turbo- and Supercharging

Manipulations of the vascular pedicle(s) have been termed "turbocharging" or "supercharging."[46] When two independent pedicles of a "conjoined flap" are joined to each other before anastomosis to recipient vessels, it is termed "turbocharging." The two independent pedicles may be from two adjacent angiosomes or perforasomes. In the author's opinion, the "turbocharge" creates a "neo-vasculosome" and overcomes the interruption in the "vascular axis" inherent to a "conjoined flap." For example, a free transverse rectus abdominis musculocutaneous (TRAM) flap may be "turbocharged" by connecting the superficial epigastric vessels to the side of the deep inferior epigastric pedicle to create a "neo-vasculosome" (by bypassing the "break" in the "vascular axis"), thereby increasing the predictability of flap survival (**Fig. 5.16**). This maneuver has been used by Koshima and the resultant flap has been termed a "mosaic connected flap."[47]

"Supercharging" of one of the pedicles of a bipedicled flap (arterial or venous), on the other hand, creates a separate pathway of arterial augmentation or venous drainage of the flap. For example, a pedicled TRAM flap being used for breast reconstruction may be "supercharged" (and/or "superdrained") by anastomosing the deep inferior epigastric artery/vein to a recipient artery/vein in the axilla or thorax to increase predictability of flap survival. When arterial supercharging is required, the flap is better termed a conjoined flap.

Manipulation of the vascular pedicle by anastomoses should not be interpreted as means of producing "new" flaps but as means of supplementing flap circulation and thereby increasing predictability of flap survival.

## Delay of a Flap

Another method of increasing predictability of flap survival is by "delay" of a flap. Gillies said that "*delaying is a method of coaxing the longitudinal vessels of the pedicle to continue onto the very end of the flap's extremity*."[48] "Delay" of a flap,

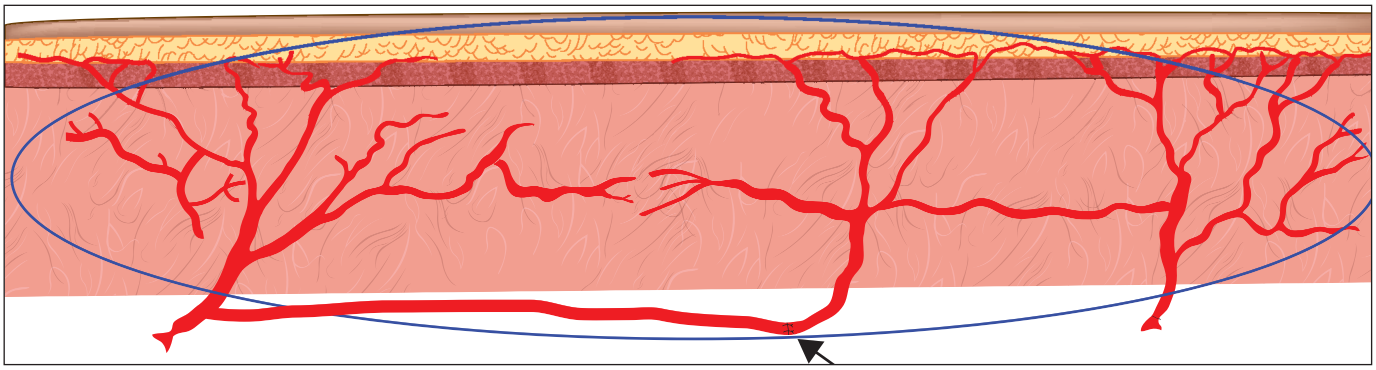


**Fig. 5.16** Neo-vasculosome (blue circle) created by turbocharging (black arrow points to the anastomosis).

at present, has been accepted as a method of increasing the vascular territory of a cutaneous flap by partially dividing the blood supply to the "extended" part of the intended flap before its complete elevation. Stranc demonstrated through clinical studies in tubed pedicle flaps that "*the main blood supply through the intact dominant end of a pedicle is usually carried by one artery. The delay operation is only effective if the main feeding artery is cut, thus reducing both the inflow and arterial inflow pressure. In response to a good delay the blood flow across the other end of the pedicle will be increased in volume and will also pass further and more quickly down the tube.*"[49] This technique of ligating the "main feeder" of a flap territory to increase "flow" from the adjacent territory has been termed "strategic" delay in contrast to the more "standard" forms of delay where only a part of the "carrier segment" of a flap was divided. In scientific parlance, "delay" would indicate "remote ischemic preconditioning" part of a flap.

Graefe was the first to describe the complete elevation of a skin flap and delayed transfer in his book *Rhinoplastice* published in the year 1818. This enabled him to directly observe complete flap survival before its transfer. Blair used the term "delayed flap transfer" for the same purpose.[50] During his clinical practice, he realized that the distal end of some flaps would undergo necrosis after elevation and transfer. Hence Blair suggested elevating the entire flap and then delaying the transfer. By his method, if the end of the flap underwent necrosis, the flap could be redesigned (by further mobilization of the pivot point) before its final transfer. In current practice, however, flap "delay" is not used in the same sense.

## Flap Prefabrication

It is a unique technique by which a suitable vascular pedicle is harvested from its bed and implanted into another "tissue unit." After a period of delay, when neo-vascularization is complete, the "tissue unit" (along with its implanted vascular axis) is harvested along with its vascular pedicle and moved to a desired recipient area as a pivot or free flap. In the author's opinion, prefabrication creates a "neo-vasculosome." Although this technique was first described by Orticochea in 1971,[51] Yao introduced the term "prefabrication" in 1982.[52] Morrison stated that "*prefabrication therefore holds the potential of making a flap with the ideal pedicle linked to the ideal donor tissue.*"[53]

# Perforator Vessels

## Anatomy of a Perforator Vessel

A perforator vessel consists of a perforating artery and its venae comitantes, which arises from a source vessel and perforates the deep fascia en route to the dermis. The size (diameter) of the venae comitantes are not always equal and sometimes there may be only one vena comitans. The term "perforator" is derived from two Latin words *per* meaning "through" and *forare* meaning "to pierce or bore."

The perforator vessel has been conveniently divided into three parts: the root, trunk, and branches (resembling a tree) by Kimura in 2003.[54] The "root" is the part of the perforator vessel that arises from the source vessel and reaches up to the deep fascia. The "trunk" is the part that exists between the deep fascia and the subcutaneous fat. The "branches" run in the subcutaneous tissue toward the dermis (**Fig. 5.17**).

Traditionally, perforator vessels have been classified based on the course of their "roots." Broadly speaking, the roots travel through or in-between muscles. Mathes and Nahai in the year 1997 classified perforators based on course of their roots into types A, B, and C.[55] The roots of type C (musculocutaneous) perforators pass through muscle, of type B (septal) perforators pass through "defined" septa, and type A (direct) perforators do not pass through any "defined" septa. In general, wherever the muscles are slender, the perforator roots tend to travel in-between the muscles (e.g., in the limbs) and are termed "direct perforators," and where the muscles are broad (e.g., the torso), they tend to travel through the muscles and are termed "indirect perforators." However, this rule of thumb has numerous exceptions.

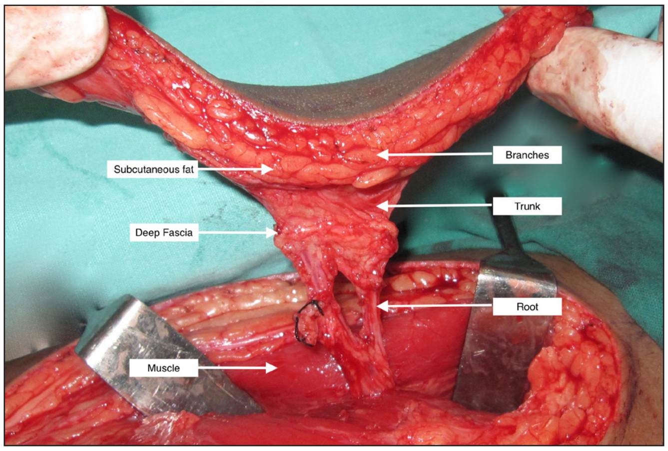



**Fig. 5.17** Demonstrating various parts of a perforating vessel (published by permission from Adhish Associates Pvt. Limited, the copyright holders).

## Nakajima's Classification of Perforator Vessels

Nakajima highlighted the importance of the "suprafascial plexus" that he termed the "fasciocutaneous plexus." This vascular network is present in the subcutaneous fat of the whole body and is fed by six types of vessels that perforate the fascia.[56] Any area of skin may be supplied by all types of perforators (in any proportion). If one type of perforator is blocked, the other perforators compensate and supply the suprafascial plexus and maintain the vascularity of the cutaneous territory. Nakajima in his article published in 1986 described six types of perforators and named them types A to F (**Fig. 5.18**).

Types A and B are relatively large perforators that pass through the fascia and run parallel or at an angle to the latter and contribute to the suprafascial plexus. Type A perforators (termed "direct cutaneous vessels") pass through subfascial fat to reach the skin (e.g., lateral thoracic artery and superficial inferior epigastric artery perforators); type B perforators (termed "direct septocutaneous vessels") pass in-between muscles to reach the skin (e.g., Radial collateral artery perforators which supply the lateral arm flap). Both types A and B perforators are capable of supporting large cutaneous flaps. It is of paramount importance to differentiate types A and B, especially during their dissection. Isolation of type A perforators requires dissecting through fat and ligating small branches to adipose tissue. On the other hand, type B perforators travel through two fascial leaves and give out multiple small branches to the neighboring muscles on both sides of the septum, making the dissection tedious.

Types C and D (up to 1.5 mm in diameter) perforators pass through the muscle fascicles before perforating the fascia. Type C perforators (termed "direct cutaneous branch of a muscular vessel") pass in-between large muscle fascicles and type D perforators (termed "perforating cutaneous branch of a muscular vessel") arise from an artery that supplies the muscle. Although differentiating the two may seem semantic,

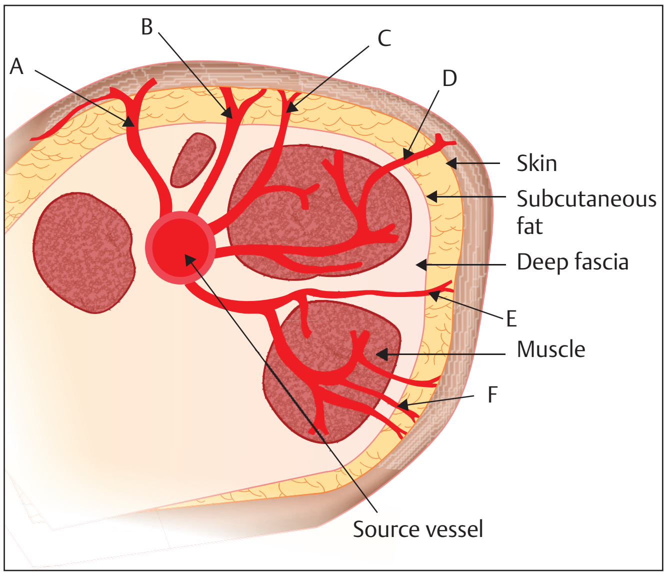



**Fig. 5.18** Classification of perforating vessels by Nakajima into types A to F.

**Fig. 5.19** Perforator flap harvested based on the direct cutaneous branch of a muscular vessel (type C perforator) (published by permission from Adhish Associates Pvt. Limited, the copyright holders).

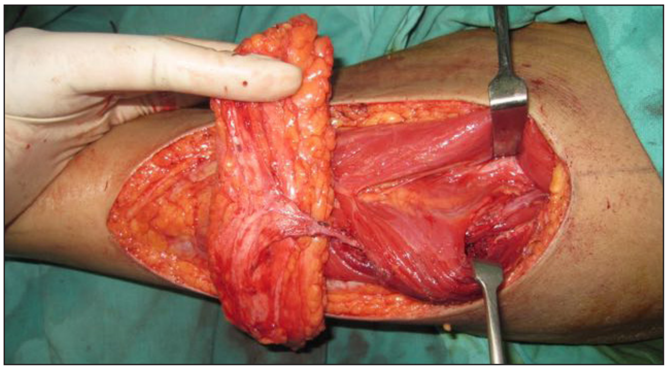


**Fig. 5.20** Perforator flap harvested based on the perforating cutaneous branch of a muscular vessel (type D perforator) (published by permission from Adhish Associates Pvt. Limited, the copyright holders).

it is of paramount importance when dissecting a "muscle perforator flap." On retrograde dissection of the perforator (from skin to the source vessel), one might observe several changes in the direction of the perforator as it branches off the muscular arteries (type D) (**Fig. 5.19**) or the perforator may have a straight course to the source vessel (type C) (**Fig. 5.20**). In the author's personal experience, the time taken and operator stress are significantly decreased in the latter. This is particularly important when raising the anterolateral thigh or the thoracodorsal artery perforator flaps.

Types E (named "septocutaneous perforator") and F (named "musculocutaneous perforator) are small-sized perforators (< 1 mm in diameter) that pass in-between muscles or through them, respectively. Both perforators feed the suprafascial plexus. For example, the skin paddle of the radial forearm flap as described by Yang in 1978 is supplied by numerous type E perforators arising from the radial artery and passing between the brachioradialis and flexor carpi radialis muscles/tendons.[57] The skin paddle of the pectoralis major myocutaneous flap, as described by Ariyan in 1979, is supplied by numerous type F perforators arising from the pectoral branch of the thoracoacromial artery. These type F perforators feed the same suprafascial plexus that is supported by the IMA perforators and the anterior intercostal artery perforators.[58]

## Taylor's Classification of Perforator Vessels Based on Suprafascial Course

Taylor and his colleagues classified perforators, based on the suprafascial directionality of perforator trunk and branch course, into uni-axial, bi-axial, and stellate perforators.[59] Consideration of this directionality and inclusion of the "vascular axis" in the flap design enables harvest of reliable cutaneous flaps and is one of the principles of the "vasculosome theory" promulgated by the author.[41]

# Perforator Flaps

A *perforator flap* is defined as any defined tissue element (skin, subcutaneous tissue, and/or deep fascia), which is supplied by a perforator vessel.

At the beginning of the current millennium, there was a raging controversy over terminology of skin flaps and some authorities viewed that the term "perforator flap" could be applied only to certain "perforators."[60] For example, Wei opined that only flaps with "isolated" and "indirect" muscle perforator vessels should be termed "perforator flaps."[61] However, others opined that classification of perforators should not depend on the technique of surgical dissection. The subsequent "consensus statement" that was published following a world conference on flap terminology in Gent, Belgium, however, clarified that any flap based on a "perforator vessel" (as defined above) should be termed a "perforator flap."[62,63] Subsequently, Wei named flaps based on "isolated" and "indirect" muscle perforator vessels and harvested by retrograde technique as "free-style perforator flaps."[64] However, because of the traditional flap harvest techniques that existed, it was difficult to classify flaps like the groin flap as described by McGregor and Jackson as a "perforator flap."

## Author's Classification of Perforator Flaps

Numerous authors have tried to classify "perforator flaps," but none have been all-inclusive. The author has attempted to classify all skin flaps based on the perforator concept. The author classifies skin flaps into two broad categories: "isolated perforator (IP) flaps" and "clustered perforator (CP) flaps." By definition, if the nourishing pedicle of the skin flap consists of dissected and isolated perforator vessel(s), it is termed an "isolated perforator" flap (**Fig. 5.21a–d**). However, if the nourishing pedicle of the skin flap includes

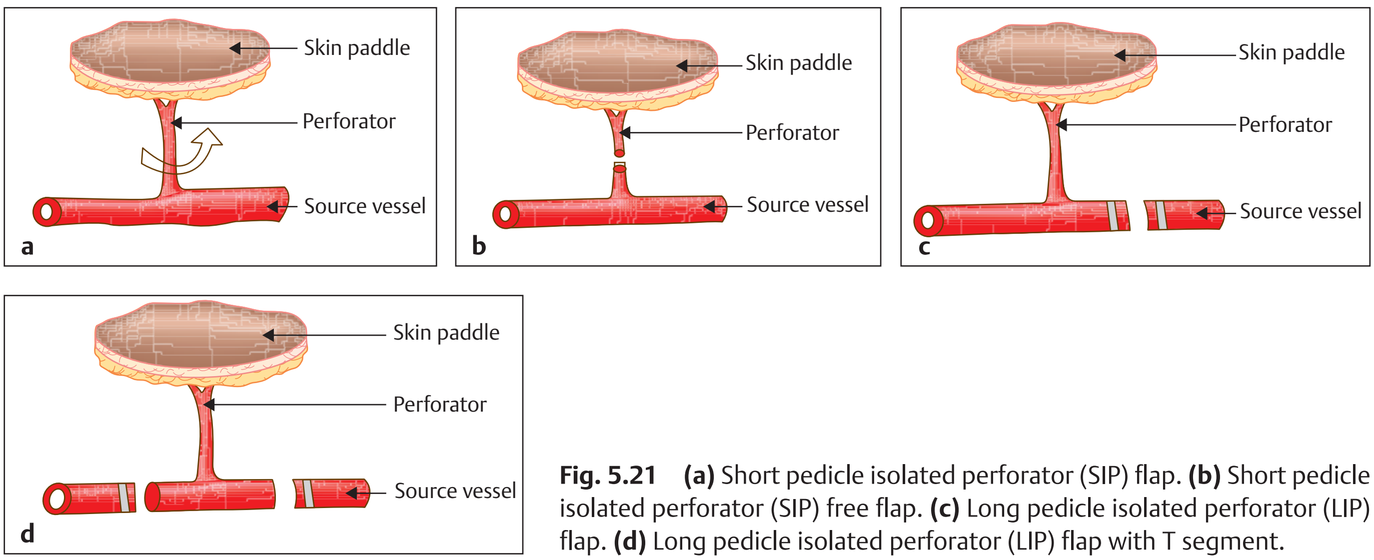



**Fig. 5.21** **(a)** Short pedicle isolated perforator (SIP) flap. **(b)** Short pedicle isolated perforator (SIP) free flap. **(c)** Long pedicle isolated perforator (LIP) flap. **(d)** Long pedicle isolated perforator (LIP) flap with T segment.

single or multiple perforators (which have not been dissected or isolated), the flap is termed a "clustered perforator" flap (**Fig. 5.22a–e**) (**Table 5.2**). This classification does not include "compound flaps."

The harvest of an IP flap includes three important steps: choosing an appropriate perforator, designing a skin paddle supported by the chosen perforator, and dissecting an adequate length of vascular pedicle as per the requirements of the defect. The first step is, therefore, of paramount importance. Traditionally the "gold standard" diagnostic modality has been intraoperative exploration of the perforator at the point where it perforates the fascia. This method of perforator selection should be termed "free-style" perforator *exploration* and the flap harvested termed a "free-style" perforator flap (a term introduced by Asko-Seljavaara).[65] When a computed tomographic (CT) angiogram is performed as a preoperative imaging tool for perforator identification prior to flap elevation, the flap is termed an "image-guided" perforator flap.[66] Image-guided perforator flaps have been shown to have advantages over "free-style" perforator flaps in certain clinical situations.[67]

The technique of dissecting a muscle perforator vis-a-vis a "septal" perforator flap differs only in the dissection through the muscle or surrounding fascial condensations respectively. However, the time taken and technical considerations required for dissection through either tissues are the same. Exploration and identification of the perforator and dissection of the source vessel remain identical whether it is a muscle or a septal perforator flap. Hence, the differentiation of the flaps based on surgical technique appears to be artificial.

## Classification of Flaps

To understand flaps, the traditional systems of flap classification need to be studied. These systems of classification were promulgated to aid reconstructive surgeons in choosing a "flap" for a particular "defect."

### Classification of Skin Flaps by Cormack and Lamberty (1984)

This classification system divides all flaps that include an element of skin into three categories as those supplied by "direct cutaneous vessels," "musculocutaneous vessels," and "fasciocutaneous vessels."[68] Although categorization of flaps under such broad groups was simple, this classification system was borne out of the "three techniques of flap harvest" described at the time and not a classification based on the anatomy of the perforating vessels. Nevertheless, Cormack and Lamberty's classification was the first significant step toward achieving a comprehensive classification of flaps including the skin. The details of the classification system have been summarized in **Table 5.3**.

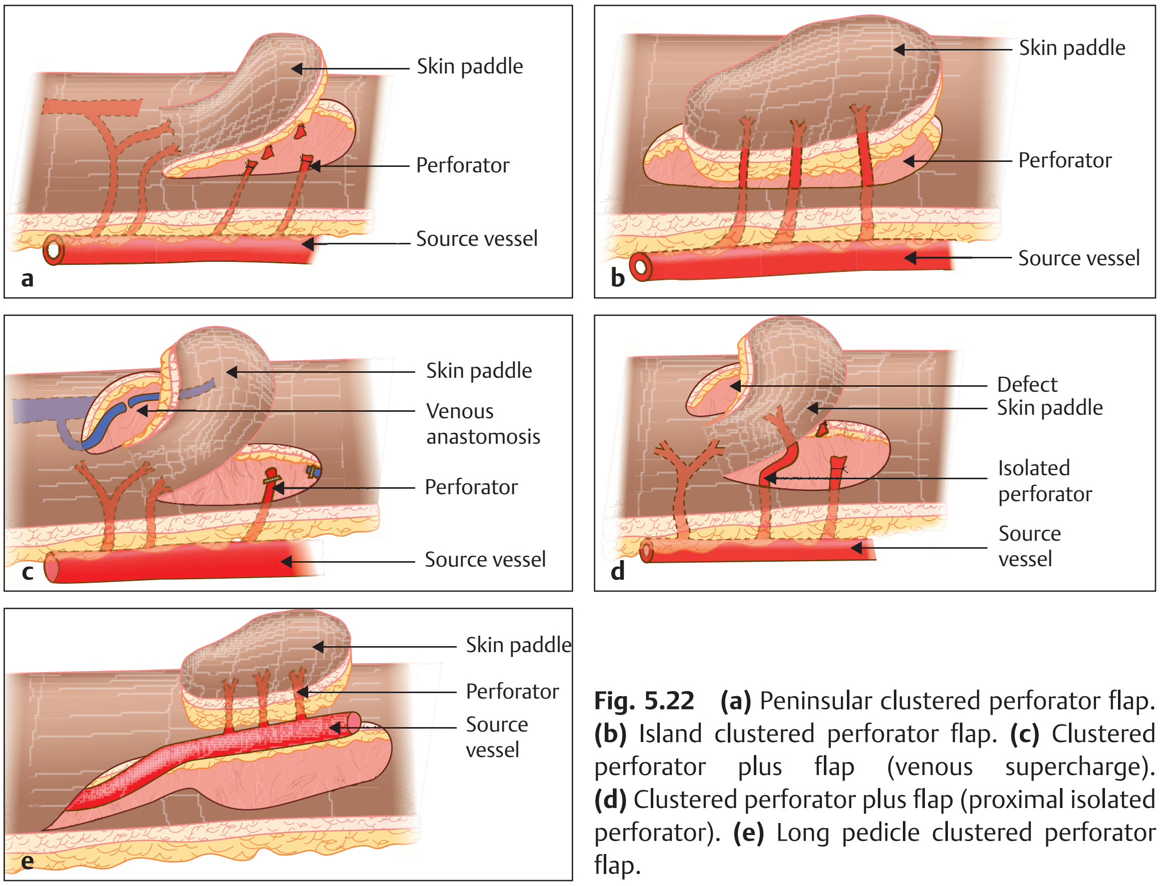



**Fig. 5.22** **(a)** Peninsular clustered perforator flap. **(b)** Island clustered perforator flap. **(c)** Clustered perforator plus flap (venous supercharge). **(d)** Clustered perforator plus flap (proximal isolated perforator). **(e)** Long pedicle clustered perforator flap.

**Table 5.2** Proposed classification of skin flaps based on the perforator concept

| Type of flap | Subtypes | Description | Examples |
| --- | --- | --- | --- |
| Isolated perforator (IP) flaps | Short pedicle-IP (SIP) flap | A short length of the perforator root is dissected. Can be used as a pedicled (**Fig. 5.21a**) or a free flap (**Fig. 5.21b**). However, when used as a free flap, super microsurgery techniques (as described by Koshima et al) are required for anastomoses.[83] | 1. "ad hoc" perforator flap (e.g., V-Y advancement design)[84,85]<br>2. Propeller flap (as described by Teo)[15] |
| | Long pedicle-IP (LIP) flap | The perforator root is dissected (retrograde) all the way to the source vessel, a variable length of which is included in the flap pedicle (**Fig. 5.21c**). A short T segment of the source artery may be used for a flow-through arterial anastomosis as described by Koshima et al[86] (**Fig. 5.21d**). | 1. Anterolateral thigh flap with perforator dissected along with a variable length of one of the branches of the lateral circumflex femoral vessels<br>2. Thoracodorsal artery perforator flap with perforator dissected along with a length of thoracodorsal vessels |
| Clustered perforator (CP) flaps | Peninsular-CP (PCP) flap (**Fig. 5.22a**) | Peninsular skin paddle design follows suprafascial directionality of the perforators. | 1. Bakamjian's deltopectoral flap[87]<br>2. Boyd's thoracoumbilical flap[88]<br>3. McGregor's groin flap[26] |
| | Island-CP (ICP) flap (**Fig. 5.22b**) | Single or multiple perforators supplying an island skin paddle. The mobility of the skin island is limited by the tethering effect of multiple perforators supplying the undersurface of the flap. | 1. Keystone design island perforator flap of Behan[89]<br>2. Subcutaneous pedicled propeller flap of Hyakusoku et al[90]<br>3. Subcutaneous pedicled flaps on the face |
| | CP-plus (CPP) flap | Peninsular-CP flap with a secondary isolated perforator at the distal part of the flap. The secondary perforator may be dissected for a long distance (termed perforator-plus flap) (**Fig. 5.22c**) or divided and transposed to a distant defect and a venous anastomosis performed (**Fig. 5.22d**). (N.B. If an arterial anastomosis is required, the flap should be renamed a conjoined flap.) | 1. "Perforator-plus" flaps in the leg (as described by Mehrotra)[91]<br>2. Venous supercharged (or rather "superdrained") TRAM flap[92]<br>3. Venous supercharged (or "superdrained") reverse-flow superficial sural artery flap.[93] |
| | Long pedicle-CP (LCP) flap (**Fig. 5.22e**) | Island-CP flap where a long pedicle of source vessel is included. The perforators are not individually dissected, but the tissue is harvested in a way to protect the perforators until the source vessel is reached. | 1. Radial forearm flap<br>2. Posterior tibial artery reverse-flow flap[94]<br>3. Posterior interosseous artery reverse-flow flap[95] |

## Classification of Skin Flaps Based on Arterial Circulation by Mathes and Nahai (1997)

This classification system defined "fasciocutaneous" flaps as per their constituent tissues, that is, fascia and skin. They stated that "*fasciocutaneous flaps with direct cutaneous (type A) or septocutaneous pedicles (type B) represent the most reliable pattern of circulation; and fasciocutaneous flaps based on pedicles through muscle (type C) usually have several pedicles at the flap base that may be less reliable.*"[69] The logical reasoning behind tripartite classification of skin flaps has not withstood the test of time as numerous perforator flaps based on vessels perforating the muscle have been described.

## Classification of Muscle Flaps Based on Arterial Supply by Mathes and Nahai (1981)

Based on "*anatomic dissections of (arteries of) cadaver (muscle) specimens injected with colored latex and radiographic evaluation of muscle specimens (with arteries) injected with latex and barium,*" Mathes and Nahai classified muscles into five subtypes.[70]

- *Type I muscle* is defined as one with a major vascular pedicle. Examples of muscles used in clinical practice are as follows: tensor fascia lata and vastus lateralis muscles (supplied by branches from the lateral circumflex femoral artery); abductor digiti minimi muscle (supplied by branch from the ulnar artery).

**Table 5.3** Classification of skin flaps by Cormack and Lamberty (1984)

| Vascular basis of flap | Name of flap | Description | Examples | Clarification |
|---|---|---|---|---|
| Flaps based on direct cutaneous vessels | “Axial” pattern flaps | The vessels included in the flap perforate through ill-defined fascial planes and run in the subcutaneous tissue parallel to the skin surface enabling harvest of “long” flaps. | 1. Groin flap as described by McGregor and Jackson.[26]<br>2. Temporal forehead flap as described by McGregor.[96] | “Axiality” is no longer a term used exclusively for direct cutaneous vessels; e.g., deep branch of the superficial circumflex iliac artery gives rise to a sartorius muscle perforator which supplies the groin perforator flap.[97] The superficial temporal artery runs in the superficial musculoaponeurotic system (SMAS) and sends small vessels to feed the suprafascial plexus of the temporal skin.[98] These flaps can be reclassified as long-clustered perforator (LCP) flaps. |
| Flaps based on septocutaneous perforators | Fasciocutaneous flaps | The vessels that nourish the flap pass through the fascial septum between muscles and then fan out to supply the overlying skin. These vessels may/may not be dissected while raising the flap. Sometimes there is no anatomical septum identified, and hence the perforators are better described as being intermuscular rather than septal perforators. | *Subtype A:* Multiple undissected septal perforators at the base of a peninsular flap. (e.g., fasciocutaneous flap described by Ponten);<br>*Subtype B:* Single constant perforator identified at the base of a peninsular flap or island flap with the source vessel dissected (e.g., medial arm flap based on the perforator from the superior ulnar collateral artery); and<br>*Subtype C:* Multiple small perforators arising from a single-source vessel and supplying the skin in a “step-ladder” fashion (e.g., the radial forearm flap based). | Ponten flaps may be reclassified as “peninsular -cluster” perforator (PCP) flaps.<br>Subtype B flaps may be reclassified as island cluster perforator (ICP) or CP-plus (CPP) flaps.<br>Subtype C flaps are also “axial” pattern flaps and may be reclassified as LCP flaps. |
| Flaps based on musculocutaneous perforators | Musculocutaneous flaps | The vessels that nourish the flap travel through a muscle and then fan out to supply the overlying skin. | The composite musculocutaneous flaps such as the rectus abdominis musculocutaneous flap, the pectoralis major musculocutaneous (PMMC) flap, and the latissimus dorsi musculocutaneous (LDMC) flap. | The muscle need not be harvested along with the skin to ensure the latter’s survival. Only the perforator(s) to the skin paddle needs to be preserved along with the source vessel to harvest a muscle perforator flap. On the contrary, a cluster of smaller perforators may be harvested along with the muscle to raise a “composite” flap like the PMMC and the LDMC flap. |

- *Type II muscle* is defined as one with dominant vascular pedicle(s) and minor pedicle(s). The minor pedicle(s) are expendable during flap elevation. Examples of muscles used in clinical practice are gastrocnemius muscle (each head supplied by medial and lateral sural arteries and minor branches from the posterior tibial artery); soleus muscle (supplied by branches from the posterior tibial and peroneal arteries); peroneus brevis muscle (supplied by branches from the peroneal artery); gracilis muscle (supplied by terminal branch of the medial circumflex femoral artery and minor branches from the deep and superficial femoral arteries); platysma muscle (supplied by branches from the external carotid artery and the transverse cervical artery); trapezius muscle (supplied by branches from the transverse cervical artery and intercostal arteries).
- *Type III muscle* is defined as one with two codominant vascular pedicles each arising from two separate regional sources. The muscle flap may be safely elevated by division of either pedicle. Examples of muscles used in clinical practice are gluteus maximus muscle (supplied by the superior and inferior gluteal arteries); intercostal muscles (supplied by branches from the aorta and IMA); pectoralis minor muscle (supplied by branches from the thoracoacromial and lateral thoracic arteries); rectus abdominis muscle (supplied by superior epigastric and deep inferior epigastric arteries); serratus muscle (supplied by branches from the lateral thoracic and the thoracodorsal arteries); temporalis muscle (supplied by branches from the maxillary and the superficial temporal arteries).
- *Type IV muscle* is defined as one with segmental vascular pedicles. Each similar-sized pedicle supplies only a small segment of the muscle and there is generally no continuous vascular axis along the entire length of the muscle. These muscles are not considered safe flap options in clinical practice. Examples of type IV muscles include external oblique, sartorius, flexor hallucis longus, and tibialis anterior.
- *Type V muscle* is defined as one with a single dominant vascular pedicle (entering close to the insertion) and secondary segmental vascular pedicles (entering close to the origin). This muscle may be elevated as a flap based on the dominant vascular pedicle or when based on multiple segmental pedicles. Examples of muscles used in clinical practice are as follows: latissimus dorsi muscle (supplied by the thoracodorsal and multiple lumbar artery perforators); pectoralis major muscle (supplied by branches from the thoracoacromial artery and multiple IMA perforators); internal oblique muscle (supplied by deep circumflex iliac artery and multiple lumbar artery perforators).

## Classification of Muscle Flaps Based on Nerve Supply by Taylor (1994)

Based on anatomical dissections of cadaver muscles and intra-arterial injection of radio-opaque lead oxide and gelatin, tagging of intramuscular nerves using coated wires followed by subtraction radiography, Taylor et al classified muscles into four subtypes.[71]

- *Type I muscle* is defined as one "*supplied by a single motor nerve that divides usually after entering the muscle*." Examples include latissimus dorsi, palmaris longus, and plantaris.
- *Type II muscle* is defined as one supplied by a single motor nerve that divides before entering the muscle. Examples include gluteus maximus, trapezius, vastus lateralis, serratus anterior, flexor carpi ulnaris, biceps brachii, brachialis, and flexor hallucis longus.
- *Type III muscle* is defined as one supplied by "*multiple nerve branches derived from the same nerve trunk*." Examples include gastrocnemius, soleus, tibialis anterior, triceps, and sartorius.
- *Type IV muscle* is defined as one supplied by "*multiple nerves derived from different nerve trunks*." Examples include elevator scapulae, internal oblique, and rectus abdominis muscle.

This classification provides a pragmatic guide to safe harvest of muscle flaps and, at the same time, preserving viable and functioning residual muscle bulk, thereby reducing donor site morbidity. For example, a skin flap "sparing" the rectus abdominis muscle (type IV) can be elevated as suggested by this classification system and as shown by Koshima and Soeda.[72] On the contrary, a tedious intramuscular dissection will be required to harvest a skin flapping the latissimus dorsi muscle (type I) as was shown by Angrigiani et al.[73]

## Classification of Vascularized Nerve Grafts Based on Arterial Supply by Terzis (1986)

Lundborg and his coworkers discovered in 1968 that nerves in rabbits are nourished by the "vasa nervorum," which originate from vessels external to the nerve (termed "extrinsic" vessels) but terminate in the epineural and intrafascicular plexus (termed "intrinsic" vessels).[74] These "intrinsic" vessels may or may not form an axis inside the nerve substance. Based on anatomical dissection of human cadaver nerves and acrylic injections of arteries, Terzis and her coworkers identified three types of nerves suitable for vascularized transfer.[74]

- *Nerves with type 1 pattern* of vessels exhibit "vasa nervorum," which are of narrow caliber and do not originate from a large-caliber "dominant" pedicle. As such these nerves (along with their nourishing vessels) are "not suitable" for microvascular transfer. Examples of type 1 pattern of vascular supply is exhibited by medial cutaneous nerves of arm and forearm.

- *Nerves with type 2 pattern* of vessels exhibit "vasa nervorum" originating from a large-caliber "dominant" pedicle that runs parallel to the nerve for "*at least a significant minority of its length*." An example of type 2 pattern of vascular supply is exhibited by the superficial radial nerve.
- *Nerves with type 3 pattern* of vessels exhibit "vasa nervorum" originating from multiple "dominant" pedicles. Examples of type 3 pattern of vascular supply is exhibited by the ulnar nerve and saphenous nerve.

Nerves with either type 2 or 3 pattern of circulation are suitable for microvascular transfer as a vascularized graft. However, the length of nerve graft that may be transferred, depends on the existing "axis" of intrinsic vessels in the nerve substance, which is fed by the extrinsic supply. The length of nerve graft that may be harvested also depends on the expendability and accessibility of donor nerves. Terzis and her coworkers, based on injection studies on cadavers, recommended that saphenous and ulnar nerves are most suited as vascularized nerve grafts.

## Classification of Vascularized Bone Flaps Based on Arterial Circulation by Serafin (1996)

Serafin classified vascularized bone flaps into two broad categories: endosteal osseous and periosteal osseous flaps.[75]

Endosteal osseous flaps are elevated with preserved nutrient vessels to the endochondral bones. Examples of these flaps include the posterior rib flap (supplied by the posterior intercostal vessels), the anterior iliac crest flap (supplied by the deep circumflex iliac vessels), and the fibula flap (when raised as a single strut of bone supplied by the nutrient vessel from the peroneal vessels).

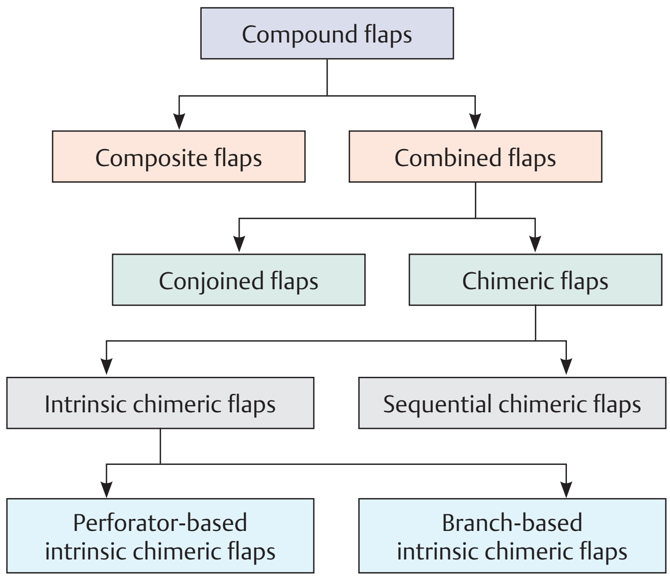
Periosteal osseous flaps are elevated with preserved periosteal branches to membranous bones. Examples of these flaps include the parietal calvarial flap (supplied by the superficial temporal vessels), the femoral condylar cortical flap (supplied by the descending genicular vessels), and the fibula flap (when raised as multiple segments of bone supplied by the segmental periosteal branches of the peroneal artery).

Strict regimentation of osseous flaps, based on their nourishing pedicle, is artificial as many of the described flaps may have both endosteal and periosteal supplies. This is especially true for the rib and fibula flaps that may receive both supplies depending on which segment of the bone has been harvested preserving the nutrient vessel and ensuring continuity of the endosteum. When osteotomies are performed, the endosteal supply is invariably interrupted and hence the segmental supply to each individual segment of bone must be maintained through the periosteal supply (**Fig. 5.23a, b**).

## Classification of Compound Flaps by Hallock

"Compound flaps" have been defined by Hallock as one that has "*incorporated diverse tissue components into an interrelated unit*." Hallock subclassified compound flaps into two broad categories: "composite flaps" and "combined flaps (**Flowchart 5.1**)."[46,76]

"Composite flaps" are those that contain multiple tissue elements en bloc and have "*a known solitary source of vascular supply intertwined within all parts that are thus dependent on each other if flap viability is to be maintained.*"[46] A composite flap is always harvested from a single angiosome. The most common example of a "composite flap" is a musculocutaneous flap such as the pectoralis major musculocutaneous flap. An oversimplistic view would be




**Flowchart 5.1** Classification of compound flap.

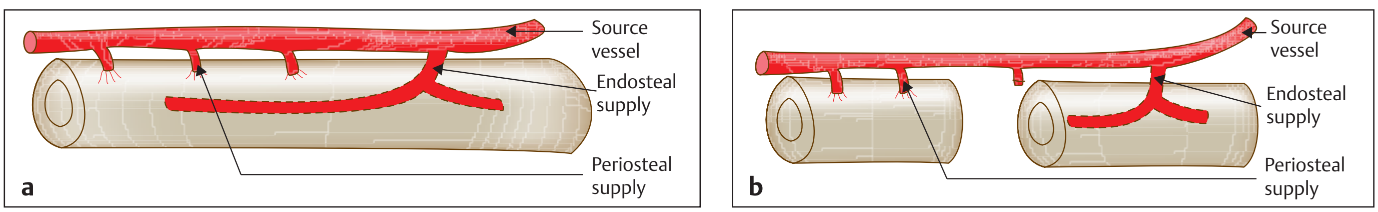



**Fig. 5.23** **(a)** Both endosteal and periosteal supply to the fibula. **(b)** Interruption of endosteal supply in the distal segment makes it dependent on periosteal supply.

to consider *all* flaps as "composite flaps" as *all* flaps have multiple tissue elements that may include the skin, subcutaneous tissue, muscle, nerve, etc. However, such an oversimplistic approach is abandoned for the purpose of this classification.

"Combined flaps," on the other hand, are those that contain multiple tissue components that have multiple sources of vascularization. "Combined flaps" have been subclassified further by Hallock into two types: "conjoined flaps" and "chimeric flaps."[76]

"Conjoined flaps," as defined by Hallock, are "combinations of at least two anatomically distinct territories, each retaining their independent vascular supply but joined by means of some common physical boundary"[46] (**Fig. 5.24a, b**). "Siamese flaps" is the politically incorrect synonym for conjoined flaps.[46] An example of this type of flap was first described by Harii when he raised a large skin flap consisting of "*a combination of latissimus dorsi musculocutaneous flap and a groin flap with either vascular pedicle (thoracodorsal vessels or the superficial circumflex iliac vessels respectively) acting as the point of flap rotation with the complimentary pedicle used to revascularize the distal end of the flap in the recipient site.*"[77] Various modifications of this technique using two (twin) or three (triplet) angiosomes have been described.[78] In the author's opinion, two or more "vasculosomes" (with their supplying pedicles) are linked together to form a conjoined flap. Bipedicle tube flaps described by Gillies are also "conjoined flaps," as they receive vascularity from both ends.

The "chimera" has been described by the Greek poet Homer in the Iliad as a hybrid composed of multiple animals. Hallock was the first to use the term "chimeric flap" to describe a flap with multiple tissue elements each with their independent vascular pedicles, joined together proximally to a "mother vessel."[79] Chimeric flaps by definition have a single common pedicle unlike "conjoined flaps" that have more than one pedicle.

The author prefers to subdivide chimeric flaps into two subtypes: "intrinsic" and "sequential" chimeric flaps."

"Intrinsic chimeric flaps"[80] or "conjoint flaps," as defined by Hallock, "*consist of multiple otherwise independently (mobile) flaps each with an independent vascular supply from a major branch that are conjoined by means of a larger common source vessel*"[46] (**Fig. 5.24c–h**). "Conjoint flaps" may be either branch- or perforator-based chimeric flaps. The author prefers to term this particular flap category as "intrinsic" chimeric flaps as distinct from "sequential"

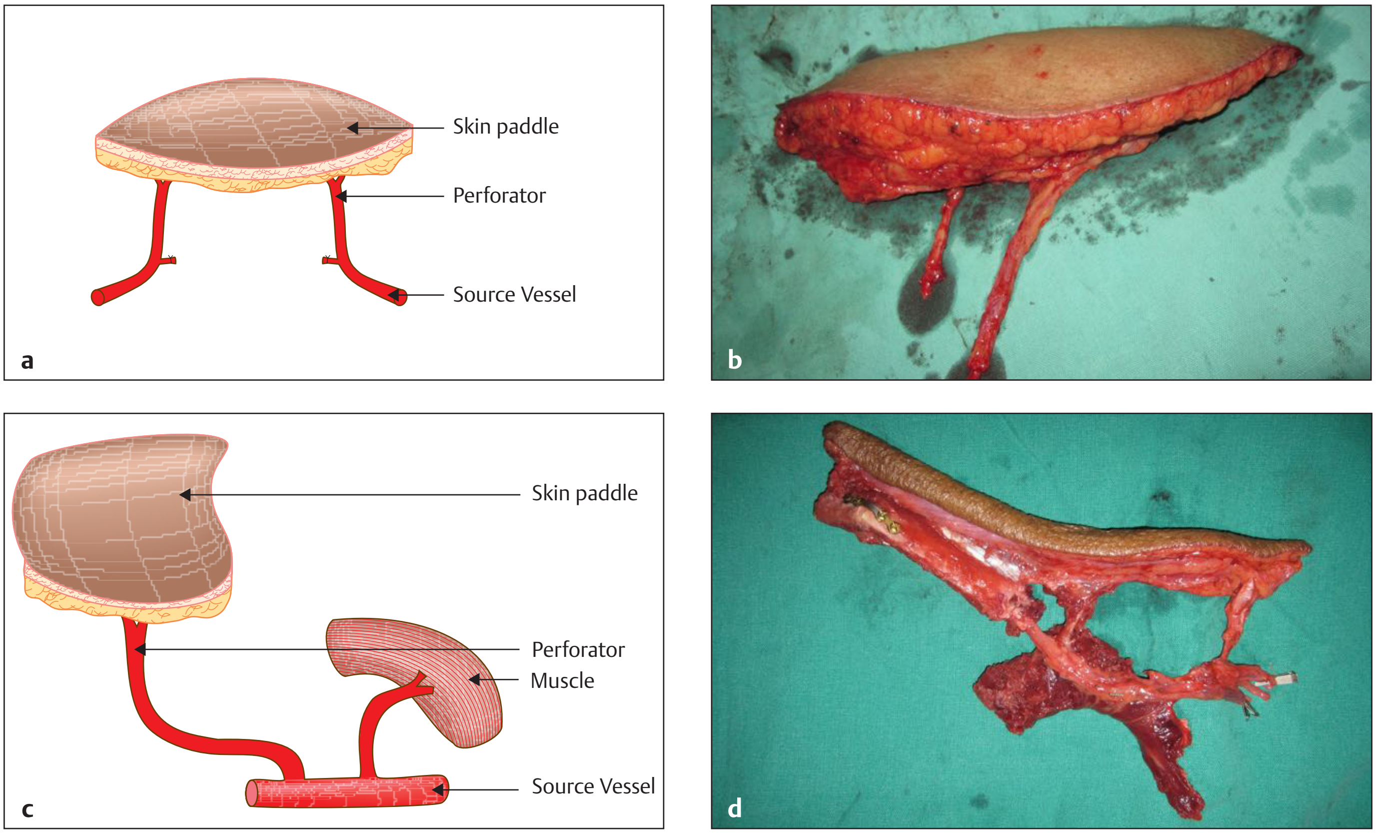


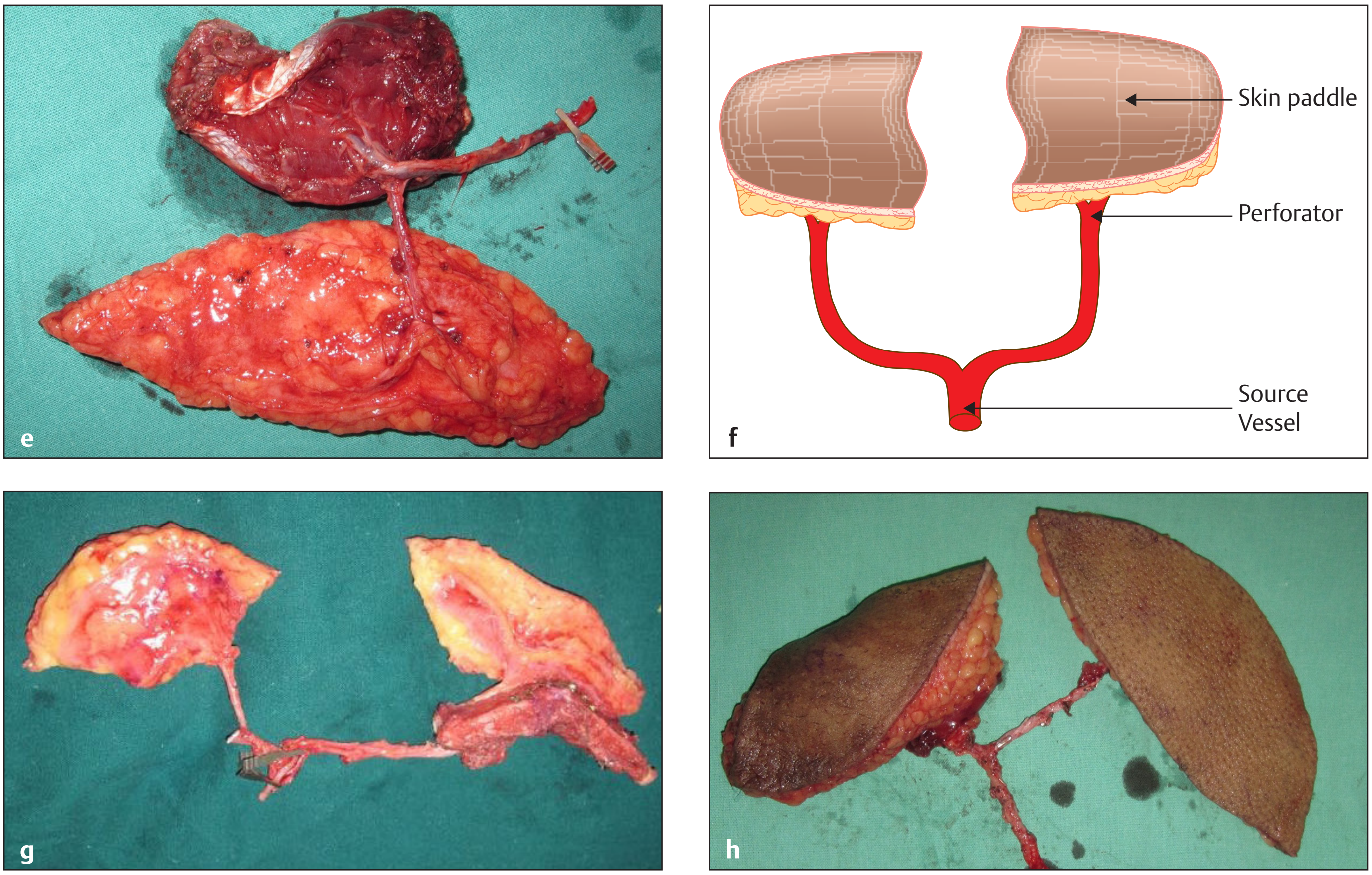

**Fig. 5.24** **(a)** Conjoined flap. **(b)** Clinical example of a conjoined thigh perforator flap requiring two separate sets of anastomoses. **(c)** Branch-based chimeric flap. **(d)** Clinical example of a branch-based chimeric peroneal artery flap with skin paddle (subsequently divided) muscle and bone. (Photographs published by permission from Adhish Associates Pvt. Limited, the copyright holders.)

chimeric flaps, the next category that are flaps "created" or "manufactured" by the microsurgeon.

"Sequential (chimeric) flaps," as defined by Hallock, are "created" when "*multiple, otherwise independent flaps, each with an independent vascular supply*," are "*joined to one another by microanastomoses*" and "*are sequentially linked together much as links on a chain*" (**Fig. 5.24i**). "Sequential flaps" have been alternatively termed "bridge," "piggy-back," and "stacked"[81] and are essentially "chain-linked" chimeric flaps. The author prefers to call this particular flap category as "sequential" chimeric flaps.

Wei and his colleagues classified chimeric flaps into three subtypes: branch-based chimeric flaps, perforator-based chimeric flaps, and chain-linked chimeric flaps.[82]

"Branch-based" chimeric flaps are those where two or more tissue elements (skin, muscle and/or bone) from an angiosomal territory are fed by individual branches directly from the source vessel (**Fig. 5.24c, d**). For example, the lateral circumflex femoral vessel-based chimeric flap with independent supplies to an island of skin and a segment of muscle (**Fig. 5.24e**). Similar chimeric flaps may be designed on the subscapular arterial system and the deep circumflex iliac system.



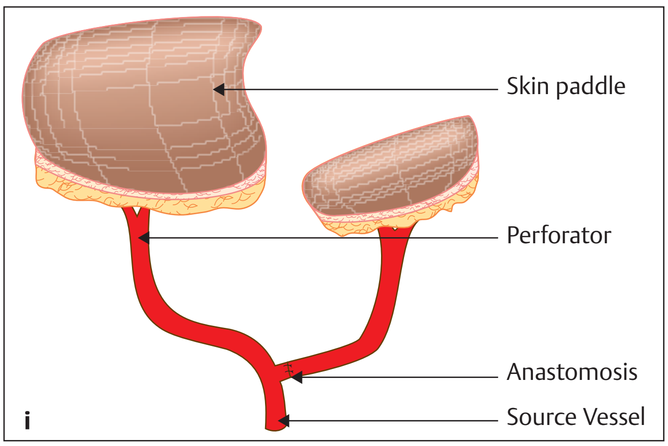




**Fig. 5.24** **(e)** The lateral circumflex femoral vessel based chimeric flap with independent supplies to an island of skin and a segment of muscle. **(f)** Perforator-based chimeric flap; **(g)** Clinical example of a perforator-based chimeric peroneal artery flap with two skin paddles. **(h)** Two skin islands fed by two separate perforators branching from the descending branch of lateral circumflex iliac vessels. **(i)** sequential chimeric flap. (Photographs published by permission from Adhish Associates Pvt. Limited, the copyright holders.)

"Perforator-based" chimeric flaps are those where two or more skin islands may be designed based on IPs, all of which join a common source vessel (**Fig. 5.24f, g**). For example, two skin islands fed by two separate perforators branching from the descending branch of lateral circumflex iliac vessels (**Fig. 5.24h**).

The author prefers to include "branch-" and "perforator-based" chimeric flap category as two types of "intrinsic" chimeric flaps.

"Chain-linked chimeric flaps" require microvascular anastomoses of two or more flaps that are ultimately linked to a single "mother" vessel. The author prefers to call this particular flap category as "sequential chimeric flaps" (**Fig. 5.24i**). The "chain linkage" may be established between two perforators, two branches, or even two source vessels.

The advantages of designing a chimeric flap are several. First, the donor site morbidity is reduced by harvesting a bespoke flap. Second, as all the different tissue elements can be inset independently in a 3D defect, the final aesthetic result is superior when compared with a single composite flap. Finally, the number of anastomoses and recipient vessels required for a "free chimeric flap" is less than if two separate flaps are designed.

The disadvantages of designing a chimeric flap are a "long" learning curve (i.e., takes a longer number of attempts to master the technique) and the requirement for meticulous preoperative planning and design.

# Conclusion

The study of flap vascularity, their classification, and applications are fascinating and cannot be completely covered in a single chapter. The readers are encouraged to read the original articles listed in the references section to thoroughly understand the concepts touched upon in this chapter.

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