8 Evolution of Soft Tissue Flaps Over Time

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Background

Most laypersons and even our medical colleagues without hesitation think that the realm of the plastic surgeon is as a cosmetic surgeon. This in a sense is correct in that the movement of body tissues anywhere for any reason by the truly aesthetic practitioner is really also a basic essential characteristic within our reconstructive domain. Even a rhytidectomy or "facelift" could be considered an advancement flap! Taken from the Dutch word "flappen" [1], roughly translated, the word "flap" refers to any hunk of tissue that has an intrinsic blood supply that will maintain its viability. Thus, a flap in addition to skin could be composed of vascularized bone, tendon, nerve, viscera, etc. The history of all such diverse flaps has already been cataloged appropriately by Dr. Koshima in the first chapter. But how they have evolved over the past millennia and why, will best here be shown concentrating on soft tissue flaps only.

8.1 Introduction

Evolution marks the changes in characteristics of a biological entity over time. To put things into the proper perspective, remember that the planet Earth is some 4.5 billion years old ± a few years! The anatomically modern human is said to be the last extant evidence of the genus Homo, which diverged from the Pan genus of the chimpanzee and bonobos—who are our DNA closet relatives still living—some four million years ago [2]. Subsequently traced from *Homo habilis* then followed by *Homo erectus* some two million years later, *Homo sapiens* finally arrived into this world only about 200,000–400,000 years ago. Exactly what "time" is can be equally misunderstood, even if a nonrelativistic discrete measurement like a "year"; and normally is conceived to always proceed in one direction—onward! But a study of the evolution of flaps requires that instead we must now go "back to the future."

Just as the evolution of *H. sapiens* was never in a straight lineage, with many divergences from and hybridizations with other concurrent species [3], so too has been the progression of flaps. To state quite simplistically the cause of this meandering, this course has long been separated into the dichotomy of the anatomists and that of the surgeons, whose paths seem to have run parallel to each other with only occasional intersections [4]. The surgeons struck first, their success [or failure] relying solely on empiri-

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Fig. 8.1 Oblique median forehead flap for two-stage repair of nasal tip

cism and geometric tissue rearrangements as convenient. The first recorded evidence of the use of flaps can be traced to the forehead flap (Fig. 8.1), circa 700 B.C., commonly used to replace the tip of the nose that often had been removed as a corporal punishment as still done in some parts of this world today. Although credit often is given to Susruta Samhita, the Kanghiara family from the Kangra District of the Northern India state of Himachal Pradesh may instead deserve this recognition, as secretly such cutaneous flaps had been used there since 1000 B.C. [5]! More than 2 millennia later, Gaspara Tagliocozzi [1597], often as he displayed in his Teatro Anatomico [anatomic theater] at the University of Bologna (Fig. 8.2), improved the Sicilian method of nasal reconstruction by cutting parallel slits in the skin over the biceps muscle to delay a bipedicled flap, one that remained attached to the arm only at both ends [6]. After a few weeks, the skin was raised to be retained only at its most distal connection on the arm, which allowed the rest to be placed upon the nasal defect itself. Only after another few arduous weeks to allow neovascularization or new blood vessel growth into the arm skin from the nose itself, the flap could be finally separated from the arm to complete the nasal repair.

In both the Indian and Italian methods of nasal reconstruction, the middle portion of the transferred flap, which allowed reach to the defect, was always left open to the air, a technique today called an *interpolation* flap. Both of these flaps, as were all of that time period, had no anatomically identified blood supply, and so were called by many "random flaps," which they were.

Key Point

In the beginning, most flaps were skin flaps designed by the individual surgeon depending on what problem needed to be solved. If the flap pattern worked, often some geometrical variation, the format could then be repeated with some reliability. These were called "random flaps," since cut at random independent of any known blood supply, and often said to be nourished by a "subdermal plexus" of vessels. Today, the proven existence of an intradermal plexus most likely is the true basis of circulation to these random flaps.

Fig. 8.2 The anatomic theatre of Gaspara Tagliocozzi today at the University of Bologna

That is not to say that the source of circulation to the muscles and skin of the body was unknown. Quain [1844] [7] knew long ago the arterial anatomy of the human body as rendered in his numerous lithographs that proved to be quite accurate (Fig. 8.3). The young medical student, Carl Manchot [1889] [8] at Kaiser Wilhelm University in Strassburg, in the highly competitive atmosphere of the day, temporarily discontinued his studies to complete cadaver dissections that unveiled the circulation to the skin to be either large arteries appearing in the fissures between muscles [now called "septocutaneous"] or by perforators through the muscles ["musculocutaneous perforators"]. With the advantage of radiography, Salmon [1936] [9] further documented the interconnections of "Les artères perforantes, musculo-cutanées," which consistently supplied specific anatomical skin territories as Manchot also had predicted. Unfortunately, these anatomi-

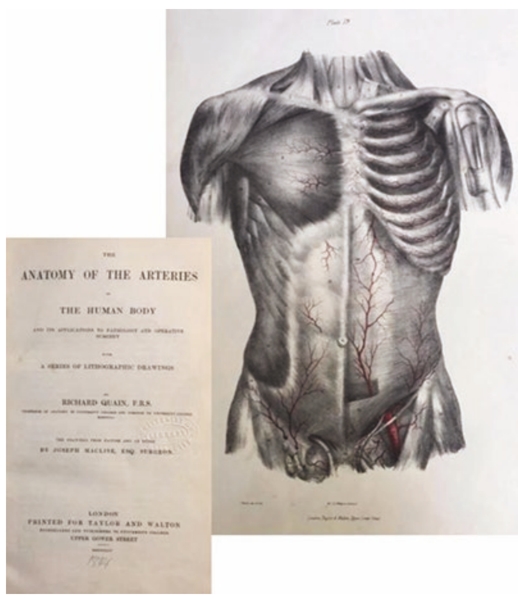

Fig. 8.3 Quain's elements of anatomy/edited by Edward Albert Schäfer and George Dancer Thane (public domain)

cal works, as were many others, were hidden from the surgeons of the English-speaking world until recently [10, 11]. For that matter, the German physiologist Spalteholz [1893] [12] was also presumably unaware of Manchot's publication, when he concluded that the primary circulation to the skin was either by direct cutaneous arteries or reinforced by small indirect vessels that emerge through the deep fascia as spent terminal branches, which had first supplied the deeper tissues and that most often muscle—in fact retrospectively corroborating the findings of Manchot and then later Salmon!

Key Point
Whenever one thinks that their personal discovery is a new revelation that will change the course of reconstructive surgery, it is prudent to investigate the literature as probably someone else had already conceived that idea, although perhaps not in the same language.

Unaware of these revelations by the anatomists, the Italian surgeon Tansini [1896] [13] personally in his cadaver laboratories solved a problem of reliably closing mastectomy wounds by transfer of tissues available nearby from the axillary region. He discovered there a large "scapular circumflex" blood vessel that coursed directly to the skin, but to be safe kept attached the latissimus dorsi muscle to thereby conceive the *musculocutaneous flap* (Fig. 8.4). Soon afterward but now almost a century ago, Esser [1917] [14] in virtual anonymity raised flaps supplied by a palpable artery of the face, trunk, or even groin that he could feel with his finger. He called these "biological flaps" or "artery flaps," which were connected to the body only by their bare vascular pedicle, known now as "island" flaps [15]. Esser did emphasize that inclusion of a nearby vein was as important if not more so than the artery, if venous congestion was to be avoided [15]—a problem still difficult to overcome with cutaneous flaps even today! Another contemporary, the Italian surgeon Pieri [1918] [16], was also well aware that discrete vessels pierced the subcutaneous tissue to vascularize the skin, and by rumor, it is said he placed in a drawing all the cutaneous perforators of the body, with suggestions of how flaps could be designed to incorporate them!

The trench warfare of the First Great War soon overwhelmed the nascent plastic surgery specialty as did the onslaught of the tubed pedicle flap (Fig. 8.5), persuasively disseminated worldwide by the New Zealander Gillies (17). This was a reasonable, if not naturally occurring event, by surgically closing side-to-side the raw undersurface of the unepithelialized open pedicle flaps previously so commonly used [e.g., the forehead flap] [17]. As in the Tagliacozzi method, the arm or even the leg (Fig. 8.6) often served as the carrier for this flap from one body region to another, requiring sometimes multiple intermediate stages and transfers to allow repeated neovascularization until the final insetting, perhaps with months between each step, and always subject to partial flap necrosis at any time. To minimize that risk, rigid length-to-width ratios were dogma to be obeyed, which for example being no greater than 4::1 in the face, or 1::1 in the less well perfused lower extremity (Fig. 8.7). Unfortunately, the tubed pedicle was the classic "random flap," relying as it could only on the "subdermal plexus" of blood vessels, which represented a dead-end divergence and simultaneously retarded the evolution of the flap, as the anatomists were to prove later once again that the surgeons had been wrong.

Slowly, if not slower, other options began to appear that proved to be more reliable and more efficient than the tubed pedicle. Even the cosmetic surgeon Jacques Joseph [1931] [18] in his book on rhinoplasty included a description of a medial based deltopectoral flap from the upper chest that captured the internal mammary musculocutaneous vessels at the second or third intercostal space as its source of circulation, information he had gleaned from Manchot's treatise that had depicted the same [8]! Bakamjian [1965] [19] later wrote that this same deltopectoral flap was based on "perforators" and could be extended horizontally from the sternum to the shoulder to immediately allow reliable coverage

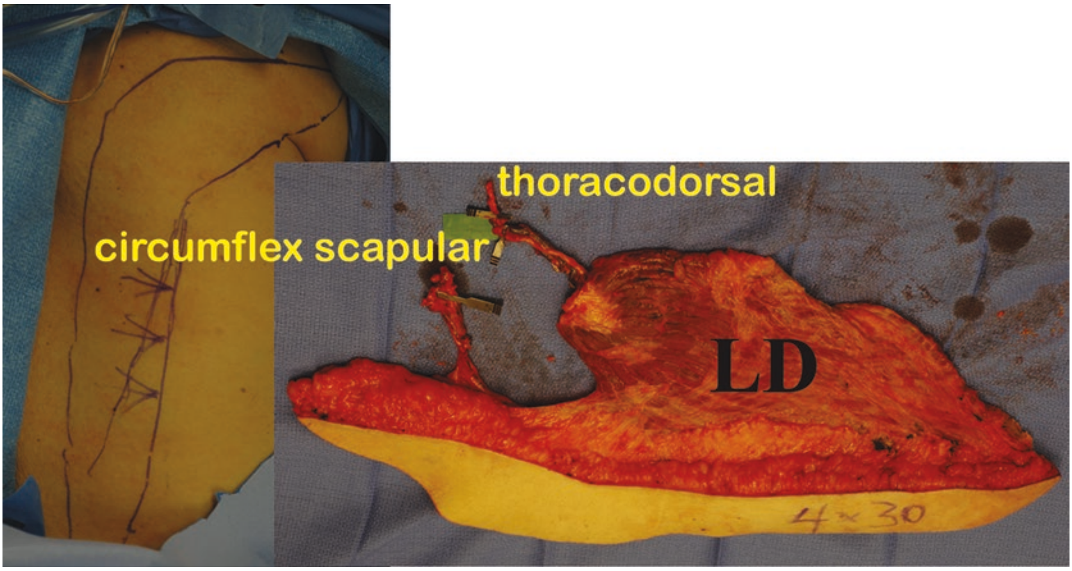

Fig. 8.4 A *musculocutaneous* flap from the back whose vascular supply is from the axilla—the cutaneous branch of the circumflex scapular to the skin, and the thoracodorsal vessels to the latissimus dorsi [LD] muscle

Fig. 8.5 Burned superior helix of the ear restored using the skin of the neck first rolled into a skinny tube, then at the second surgical step with one end still attached ["pedicled"] to the neck transferred to the ear, and finally, after many more weeks, detached from the neck to complete the reconstruction

for otherwise unsalvageable pharyngoesophageal extirpations. Milton [1970] [20] ascertained the validity of these new surgical approaches by proving in laboratory animals the fallacy of the length::width ratio of the "random flap." Instead, of greatest importance to ensure soft tissue flap viability, whether it be skin or muscle, was to know and maintain the intrinsic CIRCULATION. The anatomist had rudely intersected the path of the surgeon, and now the surgeons knew their future tact would be forever altered.

Key Point
The length-to-width ratio is a now archaic dogma that was once the reasoning behind determining how long a flap could be according to how wide or narrow was its pedicle base. This varied depending on the body region, as it was well known that the blood supply in the head and neck is far superior to that of the lower limb. As our anatomical knowledge evolved, we now know that rather than the dimensions of a flap, survival depended on what was the source of circulation that had been captured.

Among the first to straighten this new course were McGregor and Jackson [1972] [21], who sought to mimic the virtually closed arterio-venous system of the deltopectoral flap in a different body region. Perusing nineteenth-century anatomical textbooks, this pair explored the cartwheel of vessels known under the inguinal ligament where the superficial circumflex iliac arterio-venous system became their vascular basis for the oblique flap extending from the femoral triangle to the anterior superior iliac spine, which was termed the "groin flap" (Fig. 8.8). Since the nutritive vessel extended in a nearly straight line along the major axis of this elliptical flap, the appellation "axial" flap was quickly adopted. This discovery resulted in a scurry of activity. No wonder the first successful

Fig. 8.6 Skin still attached ["pedicled"] to one leg transferred to cover the exposed bone of the other as a "cross-leg" flap. After a month and development of sufficient neovascularization, the original pedicle can be divided and the legs separated

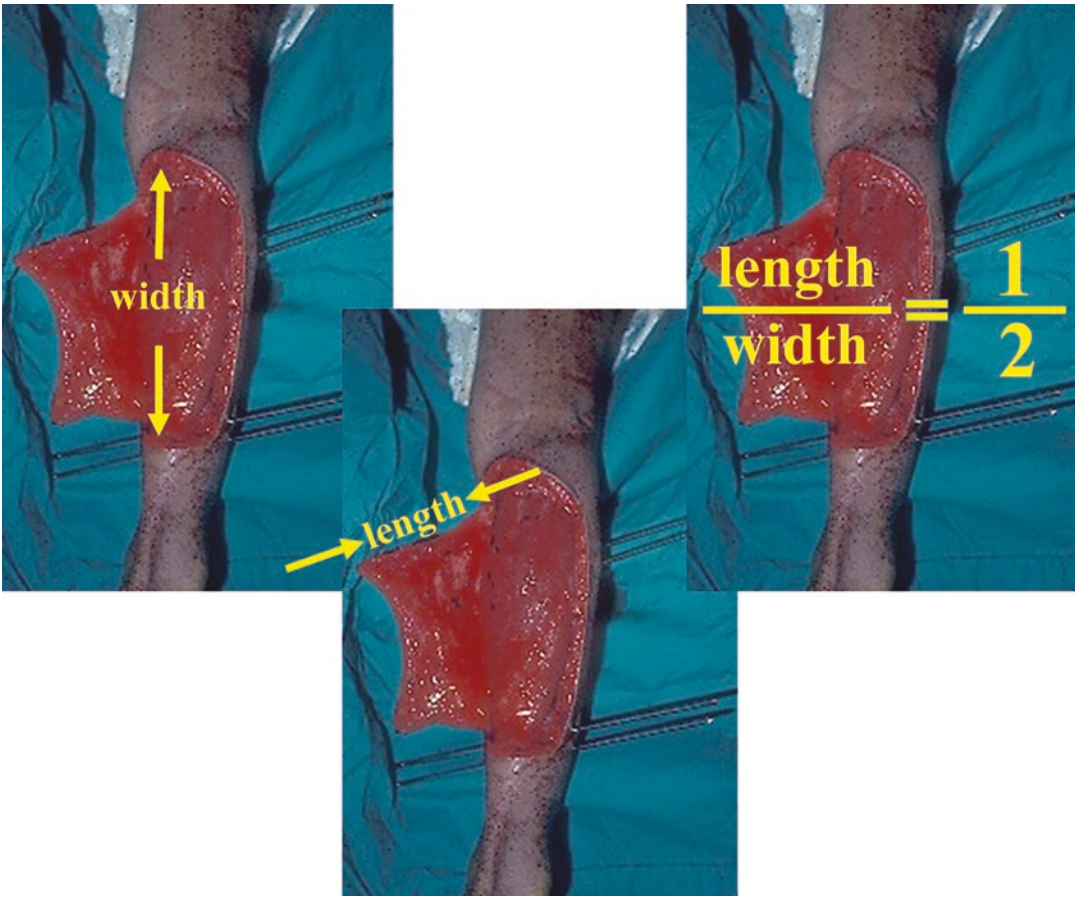

Fig. 8.7 Calf flap remaining attached to the leg only on one side like the page of a book for blood supply. The width of the base or flap pedicle is twice that of the raised length of the page, so the length::width ratio is 1:2, which in the leg should be quite reliable

Fig. 8.8 The "groin" flap can today be supplied only by superficial circumflex iliac artery perforators [SCIP], as seen lying here on the green microgrid

composite tissue "free flap" by Taylor and Daniel [1973] [22] harvested this same donor region, albeit the larger nearby superficial inferior epigastric artery was instead selected as the pedicle. Unlike other flaps, their "free flap" was temporarily totally cut free from the body to be taken elsewhere, with its artery and vein then reconnected by microanastomoses to similar vessels at a recipient site near the given defect. Without the innovative genius of Acland [23, 24] (Fig. 8.9) in customizing miniature vascular clamps, essential diminutive tools, and suture needles, the hunt would not have been as soon on for other similar free flap donor sites [25].

Key Point
A "free flap" or microvascular tissue transfer, unlike a local or regional flap, is not restricted in movement by its vascular pedicle. Instead, that can be severed, the tissue transferred elsewhere, and then the circulation reestablished after completion of microsurgical anastomoses of both flap artery and vein to those found at the new recipient site. Note that briefly this tissue has no blood supply, so in reality some could appropriately consider a "free flap" to be at least for a time a "microsurgical graft."

Even a delay in complete elevation of a flap, often used to enhance the dimensions of a tubed pedicle, could be avoided when Orticochea [1972] [26] rediscovered the musculo-cutaneous flap, a possibility he attributed to perforating branches seen to cross the deep fascia from the muscle to the skin—their existence long ago known to Manchot [8]! Note that McCraw (Fig. 8.10) and Dibbell [27] soon thereafter in their definition of independent myocutaneous vascular territories throughout the body stated that "most of the cutaneous blood supply is derived from *perforating* muscular vessels." McGregor and Morgan [28] postulated that even circulation in their "axial" pattern flap was "deriving from and draining back into the *perforating* branches" found in the superficial subcutaneous tissues. Taylor confirms this rationale on an embryological basis, describing how the nascent perforator initially penetrates the deep fascia to supply its superficial surface; and then branches in a stellate pattern toward an area of overlying skin to define its cutaneous perforator angiosome [29, 30] [the latter defined as that skin territory supplied by that perforator, or more concisely stated by Saint Cyr (Fig. 8.11) as its "perforasome" [31]]. During dynamic further pre-natal and/or post-fetal growth and move-

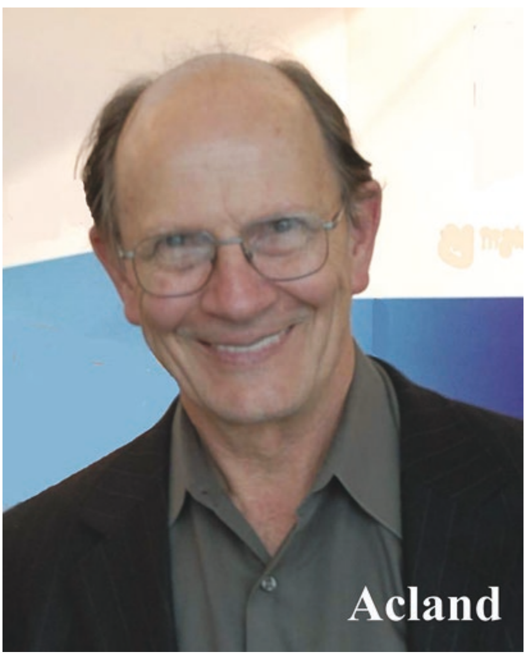

Fig. 8.9 Robert D. Acland, anatomist, microsurgeon, innovator, and "genius"

Fig. 8.10 John B. McCraw, heralded the advent of musculocutaneous perforators and myocutaneous flaps

Fig. 8.11 Michel Saint-Cyr, originator of the term "perforasome"

ment, these perforators may be stretched in one or multiple directions, which if excessive some have called *direct cutaneous* vessels [née axial], while in reality these are only a dynamic variation of the other septocutaneous perforators that were not so transformed [29, 30].

> **Key Point**
> A delay of a flap was a means to enhance the length-to-width ratio. Partially cutting sides of a flap, often in stages many weeks apart, if done properly resulted in changes in the intrinsic circulation of the flap that enhanced perfusion. Such a maneuver rarely has to be done today, as instead a donor site with the desired attributes can be immediately chosen.

To avoid the complexity of microvascular surgery, especially in the treatment of lower extremity injuries, the South African Ger [1966] advocated the use of local muscles as flaps, always keeping intact their intrinsic circulation [32]. To avoid even the use of muscles, as every muscle has a function, the Swede Pontén [1981] [33] reintroduced the "fasciocutaneous flap," which is a skin flap with the deep fascia kept on its undersurface, as another local flap alternative. Whether based on septocutaneous or neurocutaneous perforators, the length::width ratio of the local peninsula-shaped "super" flaps of Pontén in the lower limb merely by retaining the deep fascia unexpectantly exceeded 3::1 whereas traditionally otherwise should be only 1::1 [33]! Asko-Saljavaara [1983] [34] would take any adequate available suprafascial perforator to nourish a skin flap and called them "freestyle" flaps. In the following year, Song et al. [1984] [35] from China portrayed the anterolateral thigh flap that "in addition to the conventional axial flap and myocutaneous flap, we have at our disposal a new type of septocutaneous arterial flap"—although today this "ideal soft tissue" of Wei et al. [36] (Fig. 8.12) is found more often to rely on a musculocutaneous perforator.

> **Key Point**
> First intraoperatively find a perforator in a desirable donor site. Then design a flap about it. This would be a "freestyle" perforator flap. However, more often than not today, a desired perforator can be found preoperatively using a CT scan, MRI, or color duplex ultrasound. Therefore, the design of the flap incorporating that perforator can be done before the surgery even starts and is no longer "freestyle."

All this repetition about "perforators" logically led to the manuscript of Kroll and Rosenfield [1988] [37], who, at least in the English language, first used the words "perforator flap" in the title of their manuscript. However, the skin flap without the muscle of Koshima (Fig. 8.13) and Soeda

Fig. 8.12 G. Ian Taylor, first to successfully transfer a composite tissue "free flap" and anatomist extraordinaire; and Fu-chan Wei, master microsurgeon of the world!

Fig. 8.13 Isao Koshima, respected as the "father of perforator flaps"

[1989] [38] from Japan more often is credited as the beginning the *perforator flap* era. By 2012, at least by citation count, the concept of the "perforator flap" had finally become mainstream [39] in the toolbox of the surgeon, primarily due to their extraordinary ability to allow function preservation since no muscle is ever included while being selected to capture the attributes of any donor site in the body where the only prerequisite is an adequate perforator. But what really is a "perforator flap [40]?" As defined by the Gent Consensus [2003] [41] of the International Perforator Flap Faculty (Fig. 8.14), "a perforator flap is a flap consisting of skin and/or subcutaneous fat. The vessels that supply blood to the flap are isolated perforator(s)." Taylor [42, 43] emphasized in his "discussion" that followed that a "***cutaneous perforator, by definition, is any vessel that perforates the outer layer of the deep fascia to supply the overlying skin and subcutaneous tissues, regardless of its pathway from the underlying source vessel***." Of course, surgical manipulations continued to make even perforator flaps more versatile, primarily by removal layer by layer of the thick subcutaneous tissue to create the "thin perforator flap" of Kimura and Satoh [1996] [44, 45] where the deep fat layer was removed below the superficial fascia; or the "super-thin" flap of Hyakusoku et al. [1994] [46] (Fig. 8.15) where only a miniscule layer of fat is left below the subdermal plexus to preserve their subdermal vascular network flaps.

Finally, we reach the "present" time in this odyssey, finding the "pure skin perforator flap" of Narushina et al. [2018] [47] and Yoshimatsu et al. [48] (Fig. 8.16), which is a "dermal flap"—skin altogether without subcutaneous tissues! Some might argue that this is more a skin graft

Fig. 8.14 The International Perforator Flap Faculty on site in Sydney, Australia

Fig. 8.15 Hiko Hyakusoku, conceived the term "propeller flap" and investigated "superthin" perforator flaps

than a perforator flap, but unlike a graft that by definition has no blood supply whatsoever, the "dermal flap" remains supplied by a cutaneous perforator! Indocyanine green angiography has shown that the ~0.1 mm skin perforator branch as it enters to terminate within the intradermal plexus of the dermis itself has stellate reduced caliber "choke" vessels that in turn connect to those of an adjacent skin perforator branch, as well as direct "true" anastomoses, vessels without reduction in caliber, that connect adjacent intradermal branches [48]. Amazingly, this pattern reflects the angiosome concept of Taylor and Palmer [29], in that circulation is contained in a continuous three-dimensional connective tissue mesh of vessels that spans all components of the entire body! All tissues, from bone to skin in a given angiosome territory, will be served by the same source vessel so that all can be transferred simultaneously surviving only on that source pedicle as what is called a "chimeric flap" (Fig. 8.17). By definition, this form of combined flap consists of **multiple flap territories, each**

Fig. 8.16 Hidehiko Yoshimatsu, major investigator of the "pure skin perforator flap"

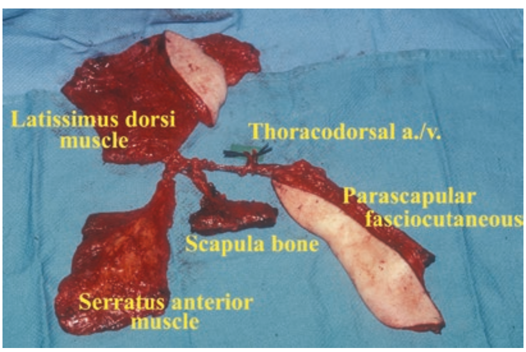

Fig. 8.17 This *chimeric* flap consists independently of a fasciocutaneous flap, musculocutaneous flap, bone flap, and muscle flap, all connected only by branches of the thoracodorsal artery [a.] and vein [v]

with their own independent vascular supply, and simultaneously independent of any physical interconnection, except where linked only by that common source vessel [49]. This penultimate surgical feat relies on an understanding of the basic anatomy to allow three-dimensional reconstructions by simultaneous transfer of multiple free flaps, yet needing only a single recipient site to connect the common vessels of the flap, and all this causing morbidity but for a single donor site!

Key Point
Compound flaps have multiple tissue constituents. If the latter are each dependent on the other for circulation, this would be a composite flap [e.g., a musculocutaneous flap]. If consisting of multiple flaps, such a combination if each flap were independent of the other except for a common source vessel would be called a chimeric flap. If the flaps are not totally independent of each other and have a common boundary, that would be a conjoined flap.

This short history of flaps, a few thousand years compared to the billions of life on Earth, has had an even briefer evolution that has been most vibrant in the past half-century. Although vascularized composite tissue allotransplantation allowing the transfer of body parts such as the face (Fig. 8.18) from one individual to another has been shown to provide superior results to conventional flap reconstructions, this is still in its early stage of development, which rightfully should be so respected and restricted to specified regional centers [50–52]. Perhaps someday a flap like this can be chosen on demand from the shelf, altogether sparing donor site morbidity, whether of "biological"

Fig. 8.18 Laurent Lantiere, Bohdan Pomahac, Eduardo D. Rodriquez, and Maria Siemionow, pioneers in facial vascularized composite tissue allotransplantations

origin as Esser would have it, or manufactured via 3D printing. Obviously, the "future" will demand extensive research by the surgeon and anatomist alike until more pragmatic alternatives become universally available. Until then and surely long afterward, the surgeon must adapt and retain sufficient flexibility in mind and skillsets for the acquisition of the best new ideas that have sustained reliability, while always minimizing complications and untoward events for their patients—indeed realizing that change is inevitable and the concept of flaps will continue to evolve ad infinitum [53] (Fig. 8.19).

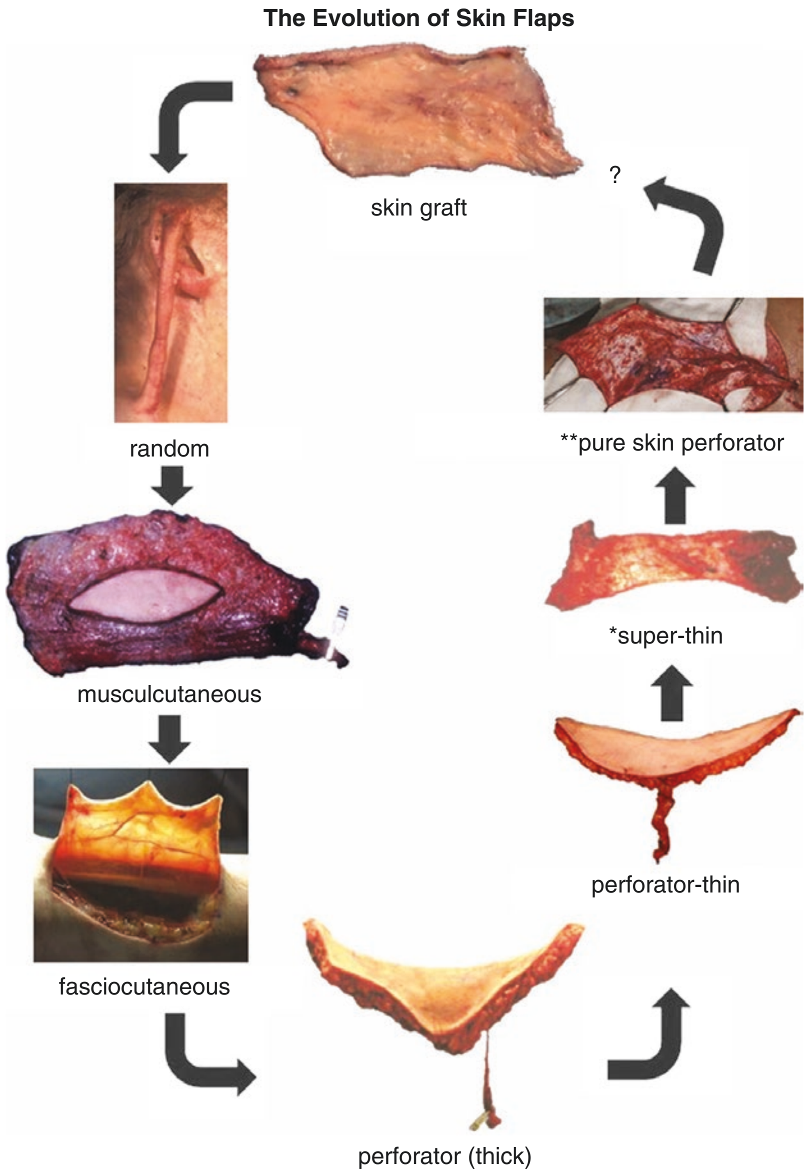

Fig. 8.19 The circumnavigation of the *Evolution of Skin Flaps*, "back to the future" and back again from the skin graft to the skin flap. [*"super-thin" flap photo courtesy of Professor Hiko Hyakusoku, M.D., Ph.D., Department of Plastic, Reconstructive and Aesthetic Surgery, Nippon Medical School, Tokyo, Japan. **"pure skin perforator flap" photo courtesy of Hidehiko Yoshimatsu, M.D., Department of Plastic and Reconstructive Surgery, Cancer Institute Hospital of the Japanese Foundation for Cancer Research, Tokyo, Japan]

Take-Home Message

- Although oftentimes a skin graft will suffice for cutaneous replacement, sometimes the wound bed cannot provide adequate nourishment to sustain it, so tissues that already have their own blood supply—and that would be a flap— will be required.
- Soft tissue flaps can be found in many forms—muscle, fascia, fat, and even just skin, or any combination of these components.
- A basic knowledge of the anatomy of the circulation throughout the body is imperative to ensure a viable flap is possible from a potential donor site. As this knowledge had expanded, so too has the scope of flaps evolved.
- Currently, the perforator flap is in vogue. These are based on a perforating vessel

of the deep fascia. A major advantage is that no muscle need be included, allowing function preservation.

- Another advantage of a perforator flap is that any body region having the desired characteristics of form and contour will suffice as a donor site—as long as an adequate perforator exists there to provide the necessary circulation.
- The pure skin perforator flap is like a full thickness skin graft, but instead vascularized by a discrete perforator. Will this be the next step in the evolution of autogenous soft tissue flaps?
- Vascularized tissue allotransplantation may be a donor source allowing superior aesthetic and functional results with no donor site morbidity, but at the present time requires immunosuppression and the constant risk of recipient site morbidity.
- In this historical journey, the nomenclature of flaps can be more than just confusing and overwhelming! Don't despair, but more specific reading will be required!

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