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Review Article

The evolution of perforator flaps and the future of microsurgery

Joon Pio Hong[a,*], Jin Geun Kwon[a], Hyunsuk Peter Suh[a], Changsik John Pak[a], Hyung Bae Kim[a], Hyun Ho Han[a], Hyungjoo Noh[b], Jae Young Hur[c], Erin Brown[d]

[a] Department of Plastic Surgery, Asan Medical Center, University of Ulsan Collage of Medicine, Seoul, Korea
[b] Department of Plastic and Reconstructive Surgery, Yas Clinic Khalifa City, Abu Dhabi, United Arab Emirates
[c] Plastic Surgery, Young Young Plastic Surgery Clinic, Seoul, Korea
[d] Department of Plastic and Reconstructive Surgery, University of British Columbia, Vancouver, Canada

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ABSTRACT

Perforator flaps have transformed reconstructive microsurgery by enabling tissue-specific reconstruction while preserving muscle, fascia, and nerves, minimizing donor site morbidity. Modern techniques—including superthin, ultrathin, and pure skin flaps—enhance flap precision, safety, and versatility. Imaging tools such as CT angiography and high-resolution ultrasound allow accurate mapping of perforator anatomy, improving flap design and outcomes. Challenges like short pedicle length and flap thickness are addressed through perforator-to-perforator supermicrosurgery, enabling anastomosis of submillimeter vessels with minimal disruption. Advances in high-magnification microscopes, ultrafine micro-sutures, robotic platforms, and digital exoscopes further expand surgical capabilities, improve ergonomics, and shorten the learning curve. Looking ahead, artificial intelligence and augmented reality promise to automate microsurgical tasks, enhance visualization, and optimize functional and aesthetic results. Collectively, these innovations are pushing reconstructive microsurgery toward the

* Corresponding author.
E-mail address: joonphong@amc.seoul.kr (J.P. Hong).

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"reconstructive elevator" ideal, achieving safer, more efficient, and highly customized outcomes for patients.
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Introduction of perforator flaps

In the era of the reconstructive elevator concept, achieving both functional and aesthetic surgical outcomes with maximal efficiency has become the standard (Figure 1).[1] However, the development of this approach was gradual. In the early days of reconstructive surgery, the primary focus was on wound closure, often without detailed understanding of flap vascularity. The importance of vascular knowledge became evident, as random-pattern flaps with unpredictable blood supply were limited in their ability to cover larger defects. The introduction of axial-pattern flaps, with defined blood supply to muscle and musculocutaneous tissue, provided a framework for flap design. Nevertheless, these flaps often required sacrificing muscle, resulting in functional donor site morbidity and undesirable bulk. In 1989, Koshima and Soeda first articulated the concept of perforator flaps, which have since gained popularity and are now considered a cornerstone of modern reconstructive microsurgery.[2,3] The concept of perforator flaps—utilizing autologous tissue while preserving fascia, muscle, and nerves to minimize donor site morbidity—was revolutionary, offering an early glimpse into the future of flap surgery.[3,4] The most frequently used perforator flaps nowadays are the deep inferior epigastric perforator (DIEP) flap, superior and inferior gluteal (SGAP/IGAP) flap mainly for breast reconstruction, anterolateral thigh (ALT) flap and the thoracodorsal artery perforator (TDAP) flap mainly for the ex-

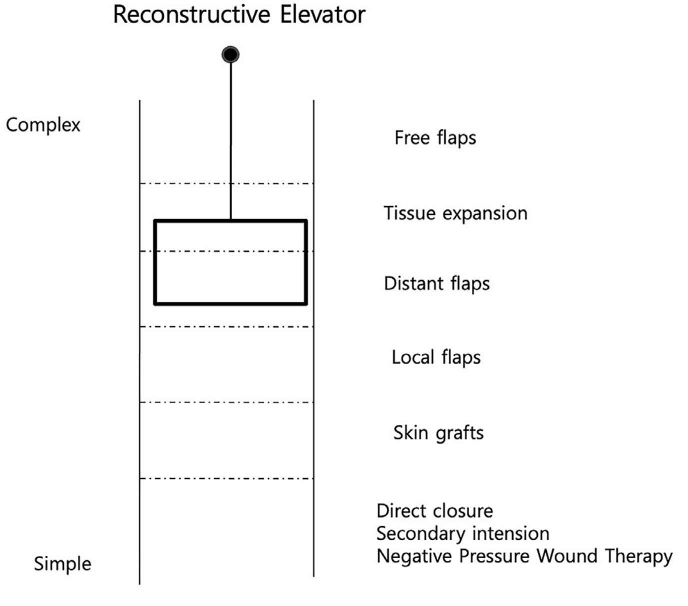

Figure 1. The reconstructive elevator concept. Unlike the ladder's sequential steps, the elevator allows surgeons to skip rungs and directly access more advanced or appropriate solutions, acknowledging that technological advances have made complex options more viable.

tremities and the head and neck region.[5–10] These perforator flaps have allowed to reconstruct the defect with the most similar tissue possible truly with minimal donor site morbidity.

Additional advantages of perforator flaps

In addition to the features mentioned above such as providing like-with-like reconstruction for resurfacing, minimizing donor site morbidity by preserving muscle function, additional advantages such as being able to provide sensation, provide long pedicles in selected flaps, ability to design versatile flaps such as chimeric style flaps, and to be able to customize according to the defect are well documented.[4,11–17] The perforator flap principle can also be used in a local flap reflecting the same versatility as being used as a free flap.[18–25]

A study by Hong et al. shows that even if the perforator flaps are not innervated, 72 % protective sensation, 21 % fine tactile, 49 % temperature, and 64 % pain peripheral sensation were present at 1 year after the reconstruction and continued to improve at 34 months.[12] The sensory recovery occurs from periphery to the central over time. Understanding the fate of sensory recovery for non-innervated perforator flaps will allow surgeons to further customize the reconstruction based on the defect and maximize efficiency, moving a step closer toward the ideal elevator approach.

A chimeric flap is constructed from multiple, distinct tissue components, such as skin, muscle, or bone, that all have independent vascular supplies but share a single, common parent blood vessel.[2,23,24] This surgical technique utilizing the vascular anatomy of perforator flaps allows surgeons to reconstruct complex defects with a single vascular pedicle, combining different tissue types to match the specific requirements of the defect site again allowing to move closer to the elevator approach.[26]

The perforator flaps provide many advantages that can be considered when selecting the flap. An algorithmic thinking allows to select the right perforator flap for different defects.[25,27] Perforator flap can be chosen based on the requirements such as pedicle length, thickness of flap, need for chimeric flap, position of the patient on the surgical table and other factors. Understanding the characteristics of the selected perforator flap allows to better reconstruct the defect.

Overcoming the limitations of perforator flaps

As quoted by Dr Fu-Chan Wei, the ALT flap has been acknowledged as an ideal flap for reconstruction due to its versatility, reliable vascular anatomy, long vascular pedicle, and minimal donor site morbidity.[9] It offers supple, durable coverage that can be tailored in size and shape for various defects across the body, from the head to the foot. Its reliable blood supply facilitates microvascular

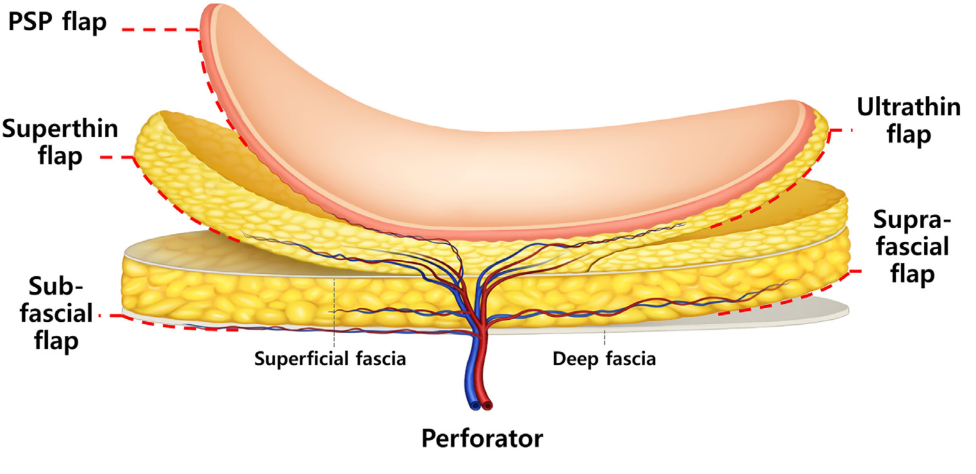

Figure 2. Various planes for elevating the perforator flap.

anastomosis, while the option to include the lateral femoral cutaneous nerve allows for sensate flaps, enhancing functional outcome.[28,29] The ability to harvest it as a two-team approach also reduces operating time, further supporting its role as a workhorse flap. In most of the perforator flap, these advantages apply to some extent as well. However, with increasing knowledge of perforator flaps and advancement of techniques, the standard for the ideal flap is steadily rising. Some may say that the linear scar on the thigh or the skin graft of the donor site after the harves may not be so aesthetically favorable. Also in relatively obese patients, the flap may be too thick to accommodate the recipient site often requiring a second stage debulking of the flap. Thus the authors searched for an inherently thinner flap such as superficial circumflex iliac artery perforator (SCIP) flap originally introduced by Dr Koshima and medial sural artery perforator (MSAP) flap introduced by Dr Cavadas to resurface shallow defects.[30–40] However, these flaps also has their limitations such as having short pedicle or limited skin dimension. Thus, various methods for thinning were introduced to avoid inaccurate reconstructions such as skin grafts on the flap margin and to over-sized skin flap to accommodate the access thickness of the flap. Although intraoperative debulking procedures are widely practiced, there is always the question of how much thinning is possible without injuring the flap vascularity.[41–44] Identifying a safe plane of elevation while preserving the vascular anatomy and flow may be the ideal approach to obtain thin flaps. Widely utilized planes of elevation are subfascial (harvesting the flap just below the deep fascia; including the deep fascia within the flap) and suprafascial (elevation is above the deep fascia) frequently still being far from obtaining a thin flap especially in obese patients. In order to safely elevate a thin flap, the authors introduced identifying and elevating the flap on the superficial fascia plane between the deep fat and the superficial fat and named it as "superthin flap."[8,45–54] New planes have subsequently been introduced such as the "ultrathin" which is elevating within the superficial fat and "pure skin" which is elevating with minimal fat attached to the flap obtaining even thinner flaps (Figure 2).[54–62] Thus the issue with bulky or thick flaps has now become less of an concern and these elevation techniques on various planes contributed a step closer to the elevator approach.[54] Furthermore, understanding the perforator and its pathway allows not only to take the flap as a pure skin flap but also allows to take a single component of the flap such as pure fat flap.[63]

A key factor in elevating thin flaps is understanding the vascular anatomy, particularly the course of the perforators. Knowing this pathway makes flap elevation both safer and more efficient. While

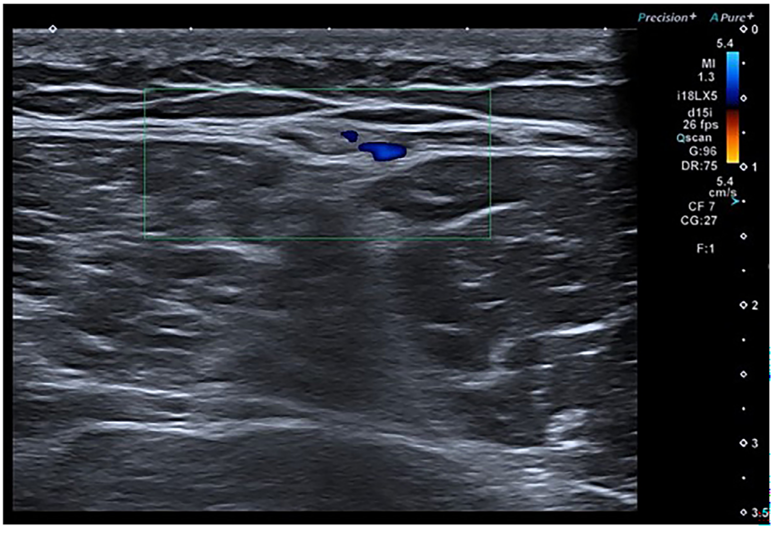

Figure 3. The ultrahigh high frequency ultrasound showing the point where the perforator penetrates the deep fascia (shown in blue in the color Doppler mode). The superficial fascia as well as the deep fascia is clearly shown.

the source vessel anatomy in perforator flaps is usually well defined, the intramuscular or subcutaneous course of the perforators can often be complex and difficult to trace. For example, in ALT flaps, microsurgeons generally know the location of the main perforator, which lies at the midpoint between the anterior superior iliac spine and the medial femoral head. However, the course of the perforator through muscle or subcutaneous fat is difficult to determine without proper imaging. With adequate radiologic evaluation, surgeons can map the perforator pathway to improve flap design and better understand its intramuscular course, which makes dissection easier. CT angiography is often used to provide this information.[64–68] As the elevation technique advanced to involve multiple layers, understanding the perforator pathway within the subcutaneous fat became essential for preserving skin vascularity. With ultrasound (Aplio i800, Canon medical systems, Tokyo, Japan), surgeons can now visualize not only the real-time course of these vessels but also their physiological characteristics, including velocity, flow volume, tissue perfusion and more (Figure 3).[20,52,69–72] The authors believe that ultrasound helps surgeons work from different planes, design chimera flaps, and understand flap blood flow, which together improve the accuracy and precision of flap design.

Opening the era of perforator flaps mixed with the concept of freestyling, the choices for perforator flaps increased immensely. Basically, any perforator can be used as a pedicel for a skin flap.[15,19,20] The challenge, however, was the pedicle length. A typical example can be the SCIP or a posterior interosseous artery perforator (PIAP) flap. Although seen as an inherently a thin flap, often the pedicle can be quite short without modification.[14,40,73] To overcome the challenges of short pedicle length, the authors introduced and advocated the perforator-to-perforator approach using the supermicrosurgery concept.[74–76] This approach allow to preserve main larger arteries without any disruption, avoids donor site morbidity by taking only a short segment of the perforator avoiding extensive dissection, increases donor site options, may provide physiologic inflow and shortens operation time opening to door to minimal invasive reconstruction.[74,76–78]

Various new innovations continue in the field of perforator flaps to not only overcome challenges intrinsic from using perforator flaps but also to increase the precision, accuracy and ultimately allowing a step further to a true elevator approach. One might question whether these innovations are merely visions of the future, distant from current surgical practice.[79,80] Yet, surgical progress has always relied on pioneers who introduce and validate new concepts, while others adopt them more

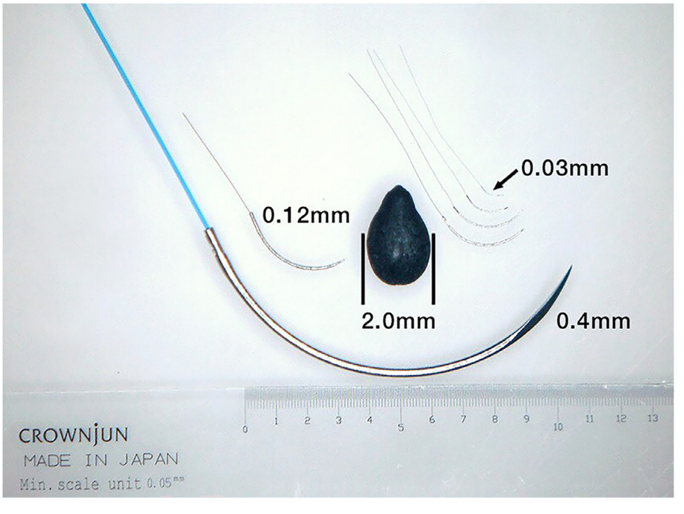

Figure 4. From the top right, that has an arrow with 0.03 mm (30 microns), it is 12–0 s, followed by 12–0, 11–0, and 10–0 underneath each needle. The needle that has 0.12 mm (120 μm) is a 9–0 microsuture. To show the relative size, a cardiovascular needle is shown on the lower part of the photo above the ruler. Image courtesy of Crownjun.

gradually due to variations in resources, training, or institutional readiness.[81–83] It remains essential, however, for followers to remain engaged with innovation, as timely adoption allows patients to benefit from safer, more efficient, and more effective treatments.

The future of microsurgery

The introduction and widespread adoption of perforator flaps created the demand for higher magnification, ultrafine microsurgical instruments, finer microsutures for small-caliber vessels, and advanced imaging modalities. Technology adapted from space telescopes has been integrated into surgical microscopes, allowing magnification of up to 77 times (MM51, Mitaka, Tokyo, Japan). Furthermore, microsutures with needles as small as 0.8 mm in length and 30 μm in diameter (12–0, Crownjun, Tokyo, Japan) have enabled anastomosis of vessels as narrow as 0.4 mm in diameter (Figure 4). Collectively, these advances have not only made perforator-to-perforator supermicrosurgery a reality but have also established supermicrosurgery as a distinct class of reconstructive surgery.[84] Many surgeons question how steep the learning curve is before one can reliably handle vessels of such small dimensions. The introduction of robotic microsurgical platforms (Symani, MMI, Jacksonville, Florida, USA) has addressed this challenge by providing surgeons—even those with modest microsurgical experience—with enhanced precision and dexterity, tremor elimination, improved ergonomics, and reduced fatigue (Figure 5).[85–87] Artificial intelligence is expected to play a key role in the future automation of microsurgery. In this context, digital microscopes and exoscopes are being introduced (ScopeEye, MedithinQ, Seoul, Korea) with robust capabilities for data collection (Figure 6). These systems provide surgeons with three-dimensional digital visualization of the operative field, with the potential to incorporate augmented reality overlays and enable real-time communication with peers during surgery. Such innovations aim to enhance precision, safety, and visualization for complex tasks, while also improving ergonomics for the surgeon.

Figure 5. The robotic microsurgery platform Symani. Note the microneedle holder and forceps attached to the robotic wrist in which the master (surgeon) controls from the console. Image courtesy of Medical Microinstruments, Inc.

Figure 6. A surgeon wearing a digital visor (Scope Eye) is shown. The visor imports the image from the versatile microscope which has a small foot print. The assistant is also seen wearing the visor together performing a lymphovenous anastomosis for a 0.4 mm caliber. The same image is also trasported to the large flat screen which can be seen in 3 dimension using a 3D glass.

Conclusion

Perforator flaps have revolutionized reconstructive microsurgery by combining versatility with minimal donor site morbidity. Advances in imaging, flap elevation techniques, and supermicrosurgery have enhanced precision, safety, and aesthetic outcomes. Robotic platforms, digital exoscopes, and emerging AI technologies promise to further improve efficiency, visualization, and surgical ergonomics. Together, these innovations are driving the field toward the "reconstructive elevator" ideal—maximizing functional restoration, aesthetics, and patient-centered results.

Declaration of competing interest

The authors have no commercial associations or financial disclosures to declare.

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