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An Evolutionary Perspective on the History of Flap Reconstruction in the Upper Extremity

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INTRODUCTION

Studying the development of flap reconstructive modalities of the upper extremity is similar to tracking the evolution of a species from its precursors. Similar to how a species evolves a niche because of environmental factors and resources that are present, the techniques of upper extremity flap reconstruction have developed primarily in response to 3 factors: trauma generated by the maiming insults of war and industry, knowledge exchange, and technology. This article presents this story from an evolutionary perspective that guides the reader through the development of each class of upper extremity flap reconstruction from the roots in ancient time to the distal branches of recent time. Readers should note the consistent theme of derivation from head and neck reconstructive methods that characterizes the early years of upper extremity flap reconstruction. This story organizes into 5 eras of time (Fig. 1). The period from antiquity to the Industrial Revolution (~1760–1820) is notable for bringing core anatomic knowledge, early principles of plastic surgery, and improvements in trauma care. The next time period spans the 1800s through the end of World War I and is most notable for key scientific breakthroughs and the propagation of plastic surgery. The following time period that is discussed is the interwar period through the end of World War II. The first Great War had generated a huge reconstructive case volume that catalyzed the maturation of plastic surgical reconstruction of the head and neck. The first applications of these plastic surgical principles to the hand after World War I marked the arrival of a new specialty: hand surgery. The next time period, the post-World War II era, is most notable for trauma from modern tools. This time period continues with an evolution upper extremity flap reconstruction that lags slightly behind that of head and neck reconstruction. Microvascular surgery also arrives during this era. It is not until the fifth time period (1990s–2010s) when flap reconstruction in the upper extremity takes a

unique course of development by combining reconstructive principles in a way not yet seen before on other parts of the body. This most recent time is also notable for the impact of evidence-based medicine in guiding the implementation of techniques that are available.

ANTIQUITY TO THE INDUSTRIAL REVOLUTION

Early Antiquity: Accumulation of Core Anatomic Knowledge and the Initial Principles of Plastic Surgery

The evolution of the specialty of plastic surgery and basis for upper extremity flap reconstruction begins in antiquity. Early Indian and Greek cultures showed enormous potential for advancing plastic surgery. Susruta of India (~1000–800 BC) described a regional pedicled flap for the nose in *Samahita*. Significant anatomic discoveries occurred in ancient Greek and Roman civilizations. Herophilus of Chalcedon (c. 250 BC) performed the first scientifically documented human cadaver dissections in Alexandria, Egypt (the only academic arena in ancient Greece where cadaver dissections were legal). Galen (131–221 AD) of the subsequent Roman culture described muscular anatomy from a perspective that was based on both his interpretation of Herophilus' records and also his dissections of animals. During Roman times, Celsus (25 AD) and Oribasius (325–403 AD) described random circulation pedicled flaps and local tissue rearrangements for the lips, nose, ears, and forehead. This era had all of the critical factors that would drive the accelerated course of evolution of upper extremity flap reconstruction seen during the early twentieth century (anatomic investigation, surgical technique innovations, and trauma from war). However, because of the language and communication barriers of this time period, the early techniques of plastic surgery during Indian and Greek cultures developed in parallel and never combined to yield an even greater advancement. The collapse of the Roman Empire ushered in the Dark Ages of Europe. This period of time is marked by frequent warfare and a virtual disappearance of urban life, bringing plastic surgery development to a standstill. Henceforth, no similar skin flap work was recorded for many centuries.

Antiquity (After the Dark Age): Rediscovery and Progress in Anatomy and Plastic Surgical Technique

The early medieval period of Europe is marked by retracing and building on the discoveries of early antiquity. Anatomic discovery, which had remained stagnant from the time of Galen's reports until exploration resumed in the twelfth to thirteenth centuries, resumed with the University of Bologna (Italy) group of anatomists. Ugo Borgognoni of Lucca and his son Theodoric of Cervia conducted human cadaver dissections on executed criminals. This practice was acceptable at the University of Bologna because it was not affiliated with the Catholic Church. Guglielmo da Saliceto (1210–1277 AD) described motor nerves for the first time. Mondino de Liuzzi (1270–1326 AD) was the first anatomist to inject colored liquids into blood vessels, a method that made study of the circulatory system possible; investigators used variants of this technique in the nineteenth and twentieth centuries to define the vascular supply of flaps elevated for reconstructive surgery. In the 1400s, European surgeons rediscovered the flap techniques of ancient India. Gustavo Branca of Italy began using the locoregional forehead flap technique of Susruta for the nose. There is speculation that the original Indian texts of Susruta had been translated to Arabic, which ultimately

traveled to Italy and the Brancas. This development marked what was likely the first international exchange of technical knowledge; one of the major factors affecting the evolution of upper extremity flap reconstruction. The exact details and dates are uncertain because the Brancas were very secretive.¹ Gustavo Branca's son Antonio began using a distant flap reconstruction for the nose as harvested from the arm, which is the first documented use of the upper extremity as a donor site for flap reconstruction. The Vianeo brothers of Calabria and Heinrich von Pfolzprundt (c. 1450) of Germany also used this technique for distant flap reconstruction of the nose. Gaspare Tagliacozzi (1545–1599), a professor of anatomy and surgery at the University of Bologna, finally published the technique with hopes of distributing it widely. However, the surgical community of that era did not embrace his technique, and the use of skin flaps died away again in the Western world. However, despite another stagnation in evolution of plastic surgical technique, anatomic knowledge relevant to flap reconstruction advanced steadily. The use of the printing press during the fifteenth to sixteenth centuries allowed wide distribution of this knowledge. Upper extremity anatomic depictions made significant advances in accuracy with the work of the Renaissance scientist-artists Michelangelo Buonarroti (1475–1564) and Leonardo da Vinci (1452–1519). Berengario da Carpi (1460–1530) of the University of Bologna produced detailed depictions of both the abdominal musculature and upper extremity vasculature. Giovanni Battista Canano of Ferrara (1515–1579) produced excellent illustrations of muscles of the upper extremity in his *Musculorum Humani Corporis Picturata Dissectio*.² During this period, the Belgian anatomist Andreas Vesalius working in Padua published *Humana Corporis Fabrica* (1543), the accuracy and detail of which led him to become known as the reformer of anatomy. Shortly thereafter, Charles Estienne's publication of *De Dissectione Partium Corporis* was released in 1545, which included the first descriptions of superficial nervous and vascular systems. At around the same time, Eustachius of Rome in 1552 was producing anatomic depictions that medical historians contend are even more accurate than, and just as important as, Vesalius' contributions, but these studies were less immediately impactful because of the delay in their publication until 1714.³ The British great William Harvey delineated the concept of arterial inflow and venous outflow in the extremities with his tourniquet experiment on the forearm and hand in his 1628 book *An Anatomical Study of the Motion of the Heart and of the Blood in Animals*. This period of time in the fifteenth and sixteenth centuries constituted the greatest leap forward of anatomic knowledge in history. This anatomic foundation was the basis for the development of flap reconstructive technique.

Limb Injuries in Antiquity

Before the Industrial Revolution, major extremity injuries with significant soft tissue damage occurred most commonly during war. Gunshot injuries accounted for a growing proportion of battle wounds from the 1400s onward. Because of ineffective hemorrhage control and inadequate measures to prevent and treat infection, major extremity injuries frequently led to death by either initial exsanguination or eventual sepsis. The fundamental principles of military trauma care and lifesaving technology had to develop before extremity reconstruction became a priority. The ancient Chinese, Greeks, and Arabs (900–1000 AD) were the first to try to treat war injuries by such measures as thermal cautery and ephedra-impregnated dressings.^{4–6} Extremity trauma surgery during the late medieval period

(1500s) only advanced as far as applying ligatures for directed hemostasis and stopping the destructive practice of treating contamination by pouring boiling hot oil on wounds.^{3,5} Prussian Hans von Gersdorff first used tourniquetlike devices for amputations in 1517,⁷⁻⁹ but at that stage extremity salvage was not a realistic goal in trauma triage and management.

INDUSTRIAL REVOLUTION TO WORLD WAR I

The 1700s to 1800s: the Industrial Revolution

The technologic advances of the Industrial Revolution in the 1770s promoted the evolution of flap reconstruction in many ways. Mechanization proved to be equally destructive to the inadvertently placed extremity as it was productive in bringing forth industrial and agricultural output.¹⁰ These extremity injuries provided case volume for extremity reconstruction. The industrial era also brought a large-scale production of war machinery that encouraged widespread use of more destructive weapons than before, and creating more extremity trauma to reconstruct. In addition to additional trauma volume for reconstruction, the Industrial Revolution marked the beginning of a more accelerated pace for dissemination of medical knowledge. With higher output printing presses now available, medical journals arrived in the 1660s and propagated technical and conceptual breakthroughs more efficiently than in any previous era. This technologic advance manifested with the increasingly common use of references to volumes of surgical literature and books by surgeons describing new techniques.^{10,11}

Developments in Surgery

This era of surgery is notable for important advances that prepared the way for the major reconstructive extremity surgeries that arrived later in the century. Eighteenth century extremity surgery is notable for the first description of a definitive debridement by Pierre Joseph Desault (1789), a French surgeon of the Napoleonic era.¹² However, this sound surgical technique for trauma inexplicably fell out of favor. As recently as the American Civil War, when 70% of traumatic injuries involved the limbs, excisional debridement was performed in as few as 3% of traumatic wounds. Amputation was the greatly favored treatment option, accounting for approximately 75% of surgeries performed during the American Civil War.^{13,14} It was not until World War I when debridement regained acceptance by the influence of the Belgian Antoine Depage.¹² Dominique Jean Larrey introduced effective trauma triage with his so-called flying ambulance during the Napoleonic Wars (1803–1815). This method addressed major trauma with highly efficient mobile medical units close to the lines of battle. The general anesthetic revolution brought about by Crawford Long (1842) and later William G. Morton (1846) was an absolute prerequisite for the lengthy reconstructive surgeries that would evolve in the twentieth century.³ Aseptic technique with carbolic acid and calcium chlorate described by The United Kingdom's Sir Joseph Lister (1867) and Hungary's Ignaz Philip Semmelweis (1847), along with sulfonamide antibiotics that became widely available in 1938,¹⁵ dramatically reduced infection rates and increased survival from trauma. ABO blood typing, discovered in 1901, yielded the lifesaving tool of blood trans-fusion in 1907.¹⁶ It was by these technologic breakthroughs and advances of trauma care that soldiers began to survive major trauma with higher frequency.¹⁷ By the start of World War II, mortality for those wounded had

decreased to 4.5% from 15% in the American Civil War,⁵ and surgeons at last had the option of pursuing limb salvage.¹⁸

Facial Reconstruction Establishes the Principles of Flap Reconstruction of the Upper Extremity

In addition to trauma caused by war, the late 1700s and 1800s are notable for an influx of facial soft tissue defects created by new extirpative approaches for treating skin cancer. This development spurred a new burst of evolution of flap reconstructive concepts that were later applied to the upper extremity. Francois Chopart of France (1743–1795) began performing advancement flaps for lip reconstruction. Joseph C. Carpue (1764–1846) reintroduced the Indian forehead flap technique that he had learned from reports from surgeons who had traveled to India.³ Surgeons such as Johann Carl Georg Fricke, Léon Tripier, Karl August von Burow, Jakob August Estlander, Robert Abbe, and Johann Friedrich Dieffenbach began using the readily available axial circulation available in the well-vascularized tissue of the face with various local and regional flaps. Their names have since become eponymous with local flaps on the face. Shrady¹⁹ and Halsted²⁰ also introduced the walking or jumping flaps for facial reconstruction in the 1890s.

Flap Reconstruction Reaches the Extremities and Trunk

Availability of medical literature now allowed the established reconstructive methods for the face to drive the subsequent evolution of reconstruction on the extremities and trunk. In 1854, years after the first distant flap to the face, Hamilton²¹ performed the first distant flap to an extremity with his cross-leg flap, treating a chronic ulcer in a 15-year-old boy with clear reference to “plastic operations” of the past.²² Hamilton²¹ also recognized and described the benefits of flap delay.^{21,23} Shortly thereafter, in 1862, Wood²⁴ described, with clear reference to the “Tagliacotian principle,” the first distant flap coverage for upper extremity defects with his axial-patterned circulation groin flap for reconstruction of a cicatricial burn scar contracture on the upper extremity of an 8-year-old girl. However, this technique did not become popular until a half-century later.^{24,25} Muscle flaps originated in 1894 with Dauriac of France and with Wolkowicz of Poland in 1895, applying the pedicled transposition concept of the face to the rectus abdominis muscle for reconstruction of abdominal hernias. Shortly thereafter, Tansini²⁶ and Ombredanne²⁷ described pedicled muscle flap transpositions of the latissimus dorsi in 1896 and pectoralis major in 1906 respectively for reconstruction of chest wall defects from breast cancer. In 1897, Carl Nicoladoni applied the distant flap concept with a pedicled thoracoepigastric flap to cover a degloved thumb.^{28,29} Nicoladoni later further developed the distant flap concept with application to finger reconstruction in his description of a pedicled second toe to thumb transfer in 1900.²⁹ In 1917, another distant flap for finger reconstruction, the cross-hand flap (substitution of ring finger for reconstruction of a thumb) was performed by J. Leonard Joyce.^{30,31} Later, in 1919, Albee³² developed an osteoplastic finger substitute that combined a bone graft with a distant flap. Albee³² also clearly indicates the source of inspiration for his technique is the “Italian plastic method.”³² It is notable that Nicoladoni had proposed Albee's reconstructive strategy years earlier, although he had never performed it.

World War I

From the perspective of upper extremity flap reconstruction, World War I was important for 2 reasons. First, it established principles of soft tissue reconstruction on the head and neck that were later used on the upper extremity. Second, the consequences of the unreconstructed upper extremities of this war convinced the medical community that hand surgery was a necessary specialty. Contributions came from Johannes Frederick Esser, Harold Gillies, Varaztad H. Kazanjian, John Staige Davis, Vilray Blair, and Robert H. Ivy, who made significant progress in the reconstruction of disfigured faces by testing and optimizing the reconstructive principles of the nineteenth century surgeons.³³ Tubed pedicled flaps were also introduced during this period by Vladimir Petrovich Filatov in 1916 and Harold Gillies in 1917. The tubed technique provided easier maintenance and better viability for distant flaps. World War I served as the proving ground and engine for propagation of the principles of plastic surgery. As Davis³⁴ stated, “at the beginning of World War I, there were, with the exception of myself, no general plastic surgeons available in the U.S.” By the time of the start of World War II, there were at least 60 practicing plastic surgeons in the United States.³⁵ World War I was characterized by a lack of treatment of hand injuries,^{36,37} as shown by only a half dozen scattered references to hand injuries from the surgical volumes documenting World War I in contrast with the 419-page volume on hand surgery produced after World War II by Bunnell.^{36,37}

WORLD WAR I TO WORLD WAR II

Interwar Period

After World War I, surgeons realized the impact of the disability caused by a major upper extremity injury. In assessing the injuries from World War I, Surgeon General Norman T. Kirk and the so-called father of hand surgery Dr Sterling Bunnell stated, “a man without a functional hand was the equivalent of a man without a hand.” By their influence, there was now a growing appreciation for the magnitude of the disabling effect of a crippled hand on an individual and the criteria by which specific hand disabilities would disqualify an individual from military service.³⁶ Thus, there was now a commitment to addressing major upper extremity trauma that would be notably present during World War II.³⁵

In the meantime, hand trauma caused by the new age of electric machines and tools of industrial work during the interwar period drove the evolution of a first generation of intrinsic hand flaps; techniques of reconstruction that reside within the limited surface area of the hand (Fig. 2).³⁸ These first intrinsic flaps used the major concepts of plastic surgery established thus far: distant flaps, advancement flaps, and transposition flaps. Gatewood³⁹ introduced the first distant flap of the hand in 1926 with the thenar flap for index fingertip reconstruction. Advancement and transposition flaps were performed in 1935 by Ettore Tranquilli Leali, an Italian surgeon who described the use of the V-Y advancement flap on the volar fingertip, which would become modified and popularized in later years as the Atasoy flap, an axially supplied version of the V-Y advancement.

World War II

The World War II era is notable for the impact of war injuries, industrial trauma, and dissemination of medical literature on the evolution of upper extremity flap reconstruction. Battle injuries from World War II presenting to the hand surgeons of this era, including Sterling Bunnell, Archibald McIndoe, Guy Pulvertaft, Harvey Allen, Ather Cleveland, Eugene Bricker, Don Pratt, Samuel B. Fowler, Major Joseph H. Boyes, Robert L. Payne, and Darrel T. Shaw, required reconstructions using the tubed pedicle flaps and distant flaps (hypo-gastric-groin flap⁴⁰ and thoracoepigastric flaps) learned from head and neck reconstruction in World War I. The expansion of manufacturing labor in World War II also generated an influx of associated hand trauma, catalyzing further evolution of the first generation of intrinsic hand flaps. Edwin DeJongh⁴¹ described bipediced advancements for volar fingertip coverage in 1942 for factory-related injuries. H. Geissendörfer of Germany, with his lateral V-Y fingertip advancement in 1943, and William Kutler of the United States with bipediced lateral V-Y advancement flaps, were inspired by the work of Tranquili-Leali.^{42,43} As medical literature became more accessible, the clear evidence of the influence of previous work became present in the cited bibliographies.

AFTER WORLD WAR II

From the standpoint of upper extremity flap reconstruction, the post–World War II period is notable for persistent evolutionary pressure from electric devices causing trauma to the hands. Access to previously published literature also facilitates re-discovery of past techniques. This era witnessed a maturation of medical technologies and techniques leading to the breakthrough technique of microvascular free tissue transfer. This time period marks the beginning of an information revolution in health care. Catalogs of archived literature provide a more accessible resource for exploring the knowledge of the past to fuel future progress.

Additional First-generation Intrinsic Hand Flaps

The increased potential for finger trauma created by the threat of machinery was shown by the spike in patents for safety measures such as guards to be built into saws and other potentially damaging machines.⁴⁴ As noted surgeon of this era Edwin DeJongh stated, “In America's large industrial plants, amputation is approaching a rarity. In the smaller jobbing shops, where safety departments are less efficient, this injury is still sadly common.” To treat these injuries, surgeons devised additional first-generation intrinsic hand flaps (see Fig. 2). Gudin and Pangman⁴⁵ reported the distant flap of the hand (the cross-finger flap) in 1950, but it was Cronin⁴⁶ who first performed these flaps in 1945 to treat injuries during World War II. The dorsolateral transposition flaps on the fingers, described by Lewin⁴⁷ in 1951, harnessed random-patterned blood supply, a concept that had been established on the face in previous years. Again, there is the effect of an increasingly accessible medical literature with techniques that were reported years earlier becoming rediscovered and popularized during this period of time. For instance, the previously reported thenar flap of Gatewood³⁹ was popularized by Flatt⁴⁸ in 1955.

Second-generation Intrinsic Hand Flaps

The persistent demand for finger reconstruction during the postwar period drove the evolution of a second generation of intrinsic hand flaps that are characterized by axially patterned blood supply. This evolution of use of axial blood supply follows the same course that had occurred in flap reconstruction of the face years earlier. The precursor to the first dorsal metacarpal artery (FDMA) flap was described by the German Hilgenfeldt⁴⁹ in 1950. However, because of the inaccessibility of the literature generated by Hilgenfeldt,⁴⁹ this flap was developed in parallel by J. William Littler and Erik Moberg's description in 1960.^{50,51} J. Holveich, Guy Foucher, and Jean-Bernard Braun modified the technique in later years into the present form of the axial-patterned FDMA flap. The analogous flag flap designed for the other fingers was reported by the French hand surgeon Vilain⁵² in 1952. It relies on an axial-pattern blood supply to allow the flap to avoid the constraint of the length/width ratio of a standard random-pattern cross-finger flap.⁵² The flag flap was further refined by Iselin⁵³ and eventually Lister.⁵⁴ John Wesley Snow, Bernard O'Brien, and Erik Moberg developed axial-pattern advancement flaps to cover even greater surface areas of fingertip or thumb tip amputations.^{55–57} Other surgeons, such as Harold Lueders, Brij Bhushan Joshi, P.J. Smith, Olayinka Ogunro, and Goro Inoue,^{58–62} modified the design of the dorsal transposition of Lewin⁴⁷ to take advantage of anatomic studies of the axial-patterned blood supply as clarified by Flint and Harrison,⁶³ Levame and colleagues,⁶⁴ and Flint.⁶⁵ Hueston⁶⁶ and Atasoy and colleagues⁶⁷ also reported a similar axially supplied rotational solution to fingertip amputations. The second-generation flaps generally provided more robust coverage with a greater distance of potential advancement and rotation than the previous first-generation flaps.

Head and Neck Concepts Translated to the Upper Extremity

The aforementioned factors of industrial trauma and accessibility of medical literature also spurred the evolution of previously established head and neck reconstructive techniques into their upper extremity forms. In 1957, McCash,⁶⁸ and Von Deilen and Coxau⁶⁹ formally described the cross-arm flap, although these investigators acknowledged that this technique had likely been used for years by plastic surgeons without ever being specifically reported in the literature. McGregor and Jackson⁷⁰ also translated the deltopectoral flap of Vahram Bakamjian and Jacques Joseph into the realm of hand reconstruction in 1970.

Free Flaps Arrive

During the 1960s, advances in several different areas combined to manifest with the arrival of free microvascular tissue transfer (Fig. 3). Julius Jacobson and Ernesto Suarez perfected vascular anastomotic technique on dogs and rabbits by 1960. To perform these anastomoses, they had modified the operating microscope from the Zeiss-Littman version that was being used for auricular surgery.⁷¹ Next, Malt and McKhann⁷² performed the first successful replantation of a forearm in 1962. Using loupe magnification, Morton Kasdan and Harold Kleinert revascularized an amputated thumb in 1963.^{73,74} Yoshio Nakayama and colleagues then completed the first free flap transfer of segments of intestine to the head and neck region in 1964. Surgeons in China performed the first extremity free flap of a micro-vascular toe to thumb transfer in 1965, but their work remained unknown to the rest of the world until

years later because of the political isolation of that time.^{75,76} In 1968, The United Kingdom's Cobbett⁷⁷ performed the first publicized toe to hand transfer with further evolution into vascularized joint transfer by 1976.⁷⁸ Free microvascular transfer of large volumes of tissue was accomplished in 1971 with Mclean and Buncke⁷⁹ transferring an omental flap to a skull defect. Shortly thereafter, Daniel and Taylor⁸⁰ accomplished the first microvascular extremity reconstruction by free transfer of a groin flap to the foot. Harii and colleagues⁸¹ of Japan subsequently performed the first microvascular fasciocutaneous transfer in the upper extremity with a groin flap to the hand in 1973. The first free musculocutaneous transfers to the upper extremity were performed in 1976 by surgeons in China transferring pectoralis to the forearm (unknown to the world until subsequent years)⁸² and Ikuta and colleagues⁸³ of Japan transferring gracilis to the forearm, both for treating Volkmann ischemic contractures by placing free-functioning muscle. The evolution of higher rungs of the reconstructive ladder of reconstruction in the upper extremity had progressed ahead of the development of the lower rungs with these microvascular transfers to the upper extremity occurring before the development of pedicled axially patterned fasciocutaneous, musculocutaneous, and muscle flaps in the upper extremity.

Free flaps would now permeate the body using various tissues as donors and recipients. Taylor and colleagues⁸⁴ Tamai⁸⁵ introduced the fibular osseous and iliac osteocutaneous flaps in 1975 and 1976 respectively, and by 1979 these flaps were being used routinely in the upper extremity.⁸⁶ The upper extremity even evolved into a free flap donor site with the radial forearm flap performed by G.F. Yang of China in 1979.^{87,88} The microsurgical progress in the People's Republic of China in the 1970s remained unknown to the rest of the world until an international delegation visited China in 1980, overcoming the political communication barrier. Hallock⁸⁹ introduced chimeric flaps (multiple different flaps harvested on the same source vessel) in 1991, and these flaps have provided effective coverage for mangled upper extremities with composite tissue requirements. Honda and colleagues⁹⁰ and Tsai and colleagues⁹¹ first designed venous flow-through flaps for small defects of the hand in the 1980s. These venous flaps have been used in both free and pedicled fashions,⁹²⁻⁹⁵ but they have remained less popular tools. The most recent iterations of free flaps include the free FDMA flap⁹⁶⁻⁹⁸ introduced by Günter Germann in 1995 and the medial femoral condyle flap introduced by Doi and colleagues⁹⁹ in 2000. The latest evolutionary branch point, the composite tissue allograft, was first attempted in 1964, resulting in failure within 3 weeks caused by acute rejection.¹⁰⁰ The first successful hand transplantation occurred in 1998. Transplantation programs and pharmacologic treatments are still being optimized.¹⁰¹

Pedicled Muscle and Myocutaneous Flaps

The use of pedicled muscle flaps in the upper extremity is notable in that it represents a use of new anatomic knowledge from McCraw and colleagues¹⁰⁷ in an application of established principles to treat the traditional problem of plastic surgery: wounds of various causes. Thus, the accessibility of medical knowledge and literature was the greatest contributing factor enabling the evolution of these flaps, which can be traced most closely to the tissue transposition concepts of early plastic surgery. Stark¹⁰² performed the first muscle transposition flaps by using the well-vascularized muscle on arms, thighs, and legs to treat

osteomyelitis in 1946. However, Stark's¹⁰² method did not become immediately popular. Years later, Ger^{103–105} popularized the muscle flap in the late 1960s with his posterior leg compartment muscle flaps for covering tibial wounds. Drawing on his knowledge of muscle flap transpositions, Ger¹⁰⁶ introduced the brachioradialis transposition flap for reconstruction of a soft tissue defect from vascular surgical repair with exposed brachial artery in 1976. The next advance for muscle flaps came with McCraw and colleagues¹⁰⁷ elucidating the vascularity of these myocutaneous flaps in 1977. The gamut of pedicled muscle flaps for reconstruction of the upper extremity defects were developed during the 1980s and 1990s. Chase and colleagues¹⁰⁸ even described intrinsic hand muscle flaps using a myocutaneous adductor digiti minimi flap for both functional and soft tissue reconstruction of a thumb vascular malformation in 1980.

Third-generation Intrinsic Hand Flaps

Through the 1970s and 1980s, intrinsic hand flaps evolved their third-generation features with the pedicled island flaps, on which surgeons tested the limits of a skeletonized axial blood supply. These flaps were often designed to provide an innervated result on healing. The main evolutionary factor during this period is the arrival of a comprehensive catalog of published medical literature in the newly revamped Index Medicus by the National Library of Medicine in 1960.¹⁰⁹ Access to previous techniques inspired the new innovations, as shown in the bibliographies of the published work of this era. The previous generation's dorsal transposition flaps were developed into sensate homodigital island flaps by Joshi.¹¹⁰ The thumb dorsal transposition flap was similarly developed into a homodigital island flap by Pho.¹¹¹ Heterodigital island flap strategies combined the pedicled reinnervation concepts of Moberg and Littler with the spare parts (fillet flap) reconstructive methods of Peacock.^{112–114} This period of time also saw further modification of the cross-finger concept producing the adipofascial cross-finger flap, which led to further homodigital use of the adipofascial turnover.^{115,116}

1990 TO THE 2010S

Perforator/Free-style Flaps Developed from Anatomic Insights

The most recent major evolutionary branch of flap reconstructive technique, the perforator flaps, arose in the late 1980s. At that time, the knowledge accumulated by free flap surgeons in combination with anatomic studies allowed this breakthrough. The studies of Carl Manchot, Michel Salmon, and Ian Taylor had depicted cutaneous circulation emanating from larger source vessels within deeper layers of fascia and muscle. Carl Manchot had performed the first studies of this type in 1889 with his injection of vessels to investigate the anatomy of both cutaneous circulation and innervation, although his technique is not clear.^{3,117–119} These studies were advanced in 1936 by French anatomist Michel Salmon who was able to show in great detail much smaller vessels than were shown by Manchot by his modified technique of intra-arterial injection of radio-opaque liquid and extensive use of radiography.¹²⁰ These studies were the foundation of the most recent investigations and descriptions of angiosomes by Ian Taylor. With these studies, Taylor provided the detailed maps for the concept that had challenged free flap surgeons for years: the arborized vascular supply of skin and fascia that emanates from various points of perforating vessels from a

main pedicle, as described by Wei and colleagues¹²¹ in 1986. These fundamental conceptual breakthroughs allowed the first perforator flap in 1989 with Koshima and Soeda¹²² using the DIEAP flaps to reconstruct extirpations of malignancy from the groin and tongue. In the upper extremity, the perforator flap concept has manifested with the lateral arm, posterior interosseous artery, ulnar artery, and radial artery perforator flaps.¹²³ In 2003, Fu-Chan Wei and Samir Mardini introduced a free-style technique of dissecting the vasculature of perforator flaps in retrograde fashion to be used in either pedicled or free flaps to allow an unparalleled tailoring of flap reconstruction to particular defects, especially in the upper extremity where minimizing the donor site defect is mandatory.^{124–128}

Fourth-generation Intrinsic Hand Flaps and the Information Revolution

The most recent era of this history of upper extremity free flap reconstruction begins with the information revolution. Internet access has become ubiquitous in developed countries. Extensive literature searches that previously required days of being physically present at a major university library could now occur in minutes in the comfort of the clinician's own home with an Internet portal. This unprecedented access to the technical detail of previously published literature is the major evolutionary influence of this era. The technical innovations that arrived during this time show a unique creativity that can be seen with the fourth generation of intrinsic hand flaps (see Fig. 2). These flaps challenged the limits of previously established modalities and combined multiple flap reconstructive principles into individual techniques. Awf Quaba and Yu Maruyama used the unique pattern of vascularity in the hand to support the previous design of the FDMA-based flaps in a reversed vascular orientation similar to reversed-flow fasciocutaneous flaps on the limbs.^{129–131} Further more, vascular islands and adipofascial flaps were viable when oriented on reversed flow on the fingers or on the palm.^{132–136} Most recently, flaps have arisen such as the spiral flap, which resembles the Orticochea scalp flaps based on the unique axial blood supply of the hand.¹³⁷ The Gi-gone flap harnesses an island pedicle-based axial supply in a double V-Y advancement reminiscent of Atasoy's concept.¹³⁸ Boomerang flaps combine the concepts of reversed flow and perforator flaps.¹³⁹ Even smaller and more technically challenging island flaps have arisen with the digital artery perforator flaps.¹⁴⁰ These flaps combine principles in a way that is not seen elsewhere on the body.

The Future: Evidence-based Practice

The first major rate-limiting factor of evolution, the availability of information, has now become the major factor driving the continued evolution of upper extremity flap reconstruction. Surgical literature detailing each innovative technique is now widely available, and a wide arsenal of surgical techniques is available for reconstructing nearly every defect. With so many tools in the arsenal for upper extremity flap reconstruction, the next major challenge, with which surgeons have been grappling for the last 2 decades, is how most effectively to implement the surgical options for upper extremity flap reconstruction. The greatest factor influencing the evolution of upper extremity flap reconstruction in this regard is the evidence-based medicine movement, which gained momentum in the 1990s. Evidence-based recommendations now govern parameters of upper extremity reconstructive outcomes such as flap loss, infection, bone healing, donor site morbidity, length of hospital stay, economics, and aesthetics. Flap choice, reconstructive

timing, wound factors, surgeon factors, and patient factors have all been queried as input variables. However, various flap reconstructions on the hand are difficult to study because the significant injuries of the hand involve a complex combination of skeletal, tendon, and nerve injuries. Therefore, it is difficult to make functional assessments on just the reconstructive modality alone. Furthermore, assessing tissue healing as an outcome variable of these surgeries is also subject to numerous uncontrolled variables of injury. There are also unsolved challenges that present themselves for upper extremity flap reconstruction. Severe cicatricial burn scarring causing impaired tendon gliding and disabling joint contracture has not found suitable reconstruction by either conventional skin grafting or more extensive excisions with flap reconstruction. The end-stage mangled hand similarly finds limited functional benefit from upper extremity flap reconstruction. Both of these disorders seem destined to be managed by composite tissue allotransplantation in the future. Vascularized groin lymph node flap transfers with progressively smaller anastomotic targets (supermicrosurgery) are on the frontier of hand surgery and plastic surgery, and outcomes analyses are still indeterminate as to the success of this technique.^{141,142} In future, these new techniques of upper extremity flap reconstruction will evolve more quickly because the factors that drive this process (access to surgical technique and interchange of ideas) have become well integrated into current surgical practice. The clinical outcome of the reconstructions will increasingly be the major factor that drives the direction of this evolution.

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KEY POINTS

- The evolution of flap reconstruction of the upper extremity can be summarized in the format of a phylogenetic tree.
- The history of upper extremity flap reconstruction can be organized into 5 major eras.
- In the nineteenth and early twentieth centuries, progress in upper extremity flap reconstruction followed the breakthroughs in head and neck reconstruction.
- From the 1990s to the present time, flap reconstructive techniques have been developed that are unique to the upper extremity.

Fig. 1. Evolution of flap reconstruction in the upper limb. A phylogenetic perspective with organization by era and influential factors.

Fig. 2.

Evolution of intrinsic hand flap reconstruction. FDMA, first dorsal metacarpal artery.

Fig 3.
Evolution of microvascular free tissue transfer in the upper limb.