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Clinical application of an expanded reverse-island flap with two dorsal metacarpal arteries and dorsal metacarpal nerves in index- and middle-finger degloving injury repair and amputation reconstruction

Mei Lin[a], Xi Zuo[b], Fen He[a], Qiuyuan Fu[a], Degui Li[c], Zhongnan Zuo[c,*]

[a]Department of Orthopedics, Foshan Hospital of Traditional Chinese Medicine, Foshan, Guangdong, China

[b]Department of Surgery, Perelman School of Medicine at the University of Pennsylvania, Philadelphia, Pennsylvania

[c]Department of Plastic Surgery, The First Peopleôs Hospital of Foshan, Foshan, Guangdong, China

* Corresponding author:

Dr. Zhongnan Zuo

Department of Plastic Surgery, The First Peopleôs Hospital of Foshan, Foshan, China.

E-mail address: 3505954129@qq.com

Summary

The dorsal metacarpal artery flap (DMAF) is irrefutable as an effective way of repairing long finger defects, and hand surgeons might consider using it for long finger reconstruction or degloved injury repair. Unfortunately, the DMAF containing a single dorsal metacarpal artery (DMA) hinders the treatment effect. The sensory restoration of long fingers and the reconstruction of phalangeal joints and tendon grafts are unsolved challenges as well. We reported our experience in reconstructing the index and middle finger by a reverse-island flap with two DMAs and dorsal metacarpal nerves (DMNs) with blood supply. We reviewed ten patients with finger-crush injuries affecting eight index fingers and two middle fingers. Degloving injuries occurred in two patients, and finger amputations occurred in eight others. Two patients received simple flap reconstruction and eight received finger reconstruction including seven from abandoned phalangeal joints and tendon grafts of the severed finger, and one from the iliac crest bone graft. All patients underwent finger reconstruction by an expanded reverse-island flap consisting of two DMAs and DMNs up to a maximal size of 9×8 cm^2. Postoperative follow-up evaluation showed a satisfactory appearance and functional recovery of reconstructed fingers. We posit that the expanded reverse-island flap involving two DMAs and DMNs constitutes a feasible and safe option for restoring a severely damaged index or middle finger, particularly for patients who are unwilling to undergo toe-to-finger transplantation to reconstruct the injured long fingers.

Keywords

Finger injury; Island flap; Reverse flap; Reconstruction; Dorsal metacarpal artery

Introduction

A degloved or destructive crush injury of the index or middle finger is a serious injury;[1,2] however, there is no definitive recommendation for the most appropriate surgical approach to treating it.[3,4] Traditional treatment methods that comprise a regional or distant flap to repair and reconstruct a severely injured finger possess certain limitations.[5,6] For example, a pedicled abdominal flap or subclavicular skin tunnel can be created to cover and reconstruct the injured finger, but it often results in unsatisfactory outcomes in appearance and functional recovery.[7,8] Other options include the transplantation of a toe-to-finger flap, which can be complicated by residual scars and functional defects of the foot.[9,10]

As microsurgeries have improved and hand surgeons have sought one-stage finger restoration, the reverse dorsal metacarpal artery flap (DMAF) has become more popular.[11-13] The maximal area of the flap harvested on the dorsal side of the hand is reported to be 9×4 cm^2, which is not wide enough to reconstruct a finger.[11,14] Based upon anatomical studies, one dorsal metacarpal artery (DMA) could only provide an adequate blood supply to a 5-cm-wide area of skin.[15,16] Therefore, we designed the expanded reverse-island flap with two DMAs and DMNs to reconstruct the damaged finger, and all patients achieved satisfactory outcomes. We herein describe our surgical methods and discuss their clinical applications.

Materials and methods

Study design and participants

We conducted a retrospective study and reviewed the patients treated for an index- or middle-finger injury at our hospital between June 2016 and June 2020. The study protocol was approved by our hospitalôs Ethics Committee.

The inclusion criteria were 1) patients aged 16 to 55 (because the epiphysis has not been completely closed in children under 16, while patients over 55 have less demand for cosmetic appearance), 2) acute degloved injury or destructive crush injury of the index finger, middle finger and 3) chronic amputation of the index and middle finger between the distal interphalangeal crease and palmar digital crease.

Study protocol and surgical procedures

The specific indications are long finger defect or long finger-degloving injury distal to the palmar digital crease when replant is not possible, and no damage or deformity of DMAs and veins. All patients underwent preoperative color Doppler ultrasonography to determine the course of the DMAs. Defected fingers were repaired by a reverse-island flap with two DMAs and DMNs, combined with one of the following surgeries: 1) simple flap repair in patients with acute degloving injury; 2) finger reconstruction in patients with acute finger amputation, and with the severed finger not suitable for replantation; 3) finger reconstruction by free iliac crest bone transplantation in patients with chronic finger amputation. All procedures were performed by the same hand surgeon under brachial plexus block unless stated otherwise.

Reverse-island flap preparation and transplantation

The reverse-island flap preparation and transplantation are shown schematically in Figure 1. The flap was designed with the axis at the two adjacent DMAs on both sides of the injured finger and rotation points at approximately 1.5 cm from the web of the finger. The flap contained DMAs, veins, and nerves. The flap was extended proximally to the LISTER node of the radius and was slightly larger than the skin-defect area of the finger. At the point where the distal end of

the flap intersected with the dorsal longitudinal axis of the finger, a teardrop-shaped flap (Fig. 3-B, black arrow) was created distally along the longitudinal axis to prevent subsequent circumferential scar contracture of the flap. The shape of the flap and two DMAs were marked and prepared for flap transplantation.

At the point where the distal end of the flap intersected with the dorsal longitudinal axis of the finger, the incision was extended distally along the longitudinal axis (Fig. 3-B, blue arrow) until it reached the wound surface in the finger. The sharp dissection was performed up to the subcutaneous fat layer, and attention should be paid to avoiding injury to the vessels and nerves. The flap based on two DMAs should be raised in the subfascial plane, including a strip of the interosseous muscle fascia with the pedicle, taking care to preserve the flap blood supply, nerves, and the rotation point of both pedicles. The above-mentioned fascial pedicle measures about 0.5cm in diameter. The two DMNs were retained in the flap, and the cutaneous branch of the DMNs was dissected for 2 cm distally and resected. The flap, which included the interosseous muscle fascia, was sharply dissected to protect the deep branch of the radial artery and the local tendon (Figure 1A). The flap was then transposed to cover the finger wound after being freed from the donor site. To cover the injured area, both pedicles of the island flap rotated 180° sagittally (Figure 1B), and then rotated 180° coronally (Figure 1C). Both pedicles were placed into the open tunnel without any tension. The two DMNs were then anastomosed to the proper digital nerves (PDNs).

Simple flap repair of acute finger-degloving injury

The injured finger was immediately thoroughly debrided. Hemostasis was achieved, and the area of the skin defect was measured. The distal ends of the two severed PDNs were separated

and marked for later anastomosis.

Flap preparation and transplantation were as described above. After the flap was transplanted to cover the degloving injury, the normal blood supply to the flap was assured. The wounds in the finger and vascular pedicle were sutured, and the donor site reached complete hemostasis and was repaired by a nearly full-thickness skin graft. A cast was applied for fixation postoperatively.

Finger reconstruction on abandoned phalangeal joints and tendon grafts in acute-finger amputation

The injured finger was immediately and thoroughly debrided, and hemostasis was achieved. The severed finger, unsuitable for replantation, was circular-resected, and its bones and tendons were preserved for future finger reconstruction. The area of the finger wound was measured, and the distal ends of the two severed PDNs were separated.

Flap preparation and transplantation were performed as described above. Based on the injuryôs extent, the boneôs broken end was cross-fixed by a metal plate, Kirschner wire, or steel wire to ensure the maximal range of motion (ROM) in the reconstructed metacarpophalangeal and interphalangeal joints. Coverage of digital amputation stump was performed. The other procedures for the donor and recipient areas were the same as above.

Finger reconstruction using the iliac crest bone graft and flap repair for chronic finger amputation

The skin was incised along the scar in the injured finger stump to expose the bone stump. The bone marrow cavity was opened, the surrounding scar tissue was removed, and hemostasis was

achieved. Based on the length of the normal finger on the contralateral side, the flap area required to reconstruct the injured finger was measured, and the distal ends of the two severed PDNs were separated.

Under epidural anesthesia, the size of the free iliac crest graft required for the reconstruction was measured based on the length of the normal finger on the contralateral side. The iliac crest graft was obtained with its bone cortex maximized. The iliac donor area was closed after hemostasis was achieved, and the wound was sutured and covered by appropriate dressings.

Flap preparation and transplantation were as described above. The free iliac crest graft was used to reconstruct the finger. The broken end of the bone was cross-fixed by a metal plate, Kirschner wire, or steel wire to ensure the maximal ROM in the reconstructed metacarpophalangeal and interphalangeal joints. A second-stage repair was performed if it was necessary to reconstruct the flexor and extensor tendons of the finger. Similarly, the donor and recipient areas were treated the same way.

Outcome measurements

At 5ï8 weeks after the operation, the finger cast was removed for all patients. Patients were encouraged to exercise to regain finger function, and clinical assessments of finger functions were obtained during clinic visits.

The sensibility of the þap was measured using IFSSH grading of sensory examination [17] and the static 2-point discrimination (S2PD) test.[18] ROM of the metacarpophalangeal joint (MCP) and proximal interphalangeal joint (PIP) were measured using a goniometer. Based on recommendations published previously,[17,19] we applied the modified score of hand function impairment to evaluate the postoperative outcome which provided comprehensive assessments of

anatomic loss, sensory function, and joint movement impairments. In the present study, we calculated and compared the pre- and postoperative hand function impairment score based on the clinical measurements and the published mathematical modelling[17].

Statistical analysis

Continuous data are presented as means ± standard deviation, and pre- and postoperative modified IFSSH score of hand function impairment measurements were compared using the Wilcoxon signed rank-sum test. All statistical analyses were conducted with GraphPad Prism 7.0 (GraphPad Software Inc., La Jolla, CA, USA). A $P < 0.05$ was considered statistically significant.

Results

We analyzed ten patients in this study: seven males and three females, with a mean age of 27.7 years (ranging from 17 to 47).

The index or middle fingers that were injured by crush injury or smash damage were not suitable for replantation, and the palm and dorsal sides of the hand were intact. Injuries were located between the distal interphalangeal crease and palmar digital crease of the fingers, with a maximally defective skin area of 8.3×7.5 cm^2.

In eight patients with index-finger injuries, two received simple flap repair, five received finger reconstructions using the severed finger, and one received finger reconstruction using the iliac crest bone graft. In addition, two patients had middle-finger injuries, and both underwent emergency finger reconstructions using the severed finger (detailed information is listed in Table 1).

All flaps in the ten patients survived. Two patients had small superficial necrosis at the tip

of the index and middle fingers, which healed after dressing changes. One patient had partial necrosis at the distal end of the flap, which healed after second-stage debridement and suturing. Three patients exhibited tension blisters at the distal end of the flap, which healed after dressing changes (Table 1).

All patients received postoperative follow-up by either letters or clinical visits. The duration of follow-up ranged between 12 to 23 months. Bone fractures were healed 2 to 3 months after the operation. The shortest postoperative time needed for sensory recovery was 7 weeks. The sensory recoveries in the long fingers were one finger (10%) with S2, three fingers (30%) with S3, and six fingers (60%) with S4. The S2PD of all 10 fingers ranged from 5 to 10 mm. The lengths of the reconstructed long fingers were close to normal, with satisfactory color and shape. The active ROM in the MCP joint reached 0°-75° after functional exercises. The active ROM in the PIP joint reached 20°-50° after the tenolysis and functional exercises. Reconstructed long fingers were able to perform opposition, holding, and pinching functions. It was found that patients were satisfied with the shape and function of their reconstructed long fingers (Figure 2-4).

Clinical follow-up evaluations showed improved finger functions, as evidenced by the significantly decreased modified IFSSH score of hand function impairment[17] postoperatively among all patients (median from 91.9 to 52.3, P=0.002) (Table 2). Assessments of the finger defect, sensory, and motor function showed significant improvements (Table 2). During follow-up visits, all patients showed satisfaction with their finger function recovery.

Discussion

Since the first report of applying the reverse DMAF to repair finger injury in 1991,[20] many

hand surgeons have adopted this surgical approach to restore finger functions.[21] Severe finger injuries typically require finger reconstruction.[22] In recent years, additional reports have shown using local hand flaps or island flaps for thumb reconstruction.[23,24] These flaps have the advantages of using the same single surgical field and only requiring one-stage reconstruction. The procedures are relatively simple and safe, with satisfactory sensory recoveries and certain hand function restorations. However, these methods entail harvesting a flap of limited size and are thus only suitable for repairing a partial thumb injury and not for degloving injuries to other fingers. These methods can also cause potential injuries to the common digital artery. Other methods to repair finger injury include using a free flap from the foot or toes, and these have achieved satisfactory outcomes in the appearance and function of the thumb.[9,10] However, these techniques are relatively complex, carry a risk of flap necrosis, and are only performed by highly experienced hand surgeons proficient in small-vessel anastomosis.

A DMAF was more recently used by surgeons to repair finger-degloving injuries.[12] Literatures depict a maximal area for a flap harvested from the dorsal side of the hand at 9 × 4 cm^2[2,11,14] whereas a flap width of 7 cm is usually required for finger reconstruction. Anatomical studies have shown that one DMA can provide blood to a 5-cm-wide skin area.[15,16] Therefore, we proposed that two adjacent DMAs might provide adequate blood supply to a flap with a width of 7 cm, which is the minimal requirement of a flap for finger reconstruction. As a result of our study, the flap with blood supply reached 9 × 8 cm^2 (Table 1), which was adequate in size for reconstructing any finger trauma. This flap has the advantages of ensuring satisfactory elasticity, a reliable blood supply, easy dissection, a less-variant vascular course, high survival, and the ability to resume sensory function. In the present study, we applied the expanded reverse flap with two DMAs and achieved satisfactory outcomes in our patients.

As the digital nerve defect in this study was relatively long, it required free nerve transplantation to be repaired. The effect of nerve transplantation without blood vessels is generally disappointing.[25-27] The main cause of the failure is ischemic necrosis of the nerve graft, and when nerve grafts are transplanted into areas with poor blood supply usually caused by scar, this becomes more apparent. The transplantation of DMNs with blood supply provides an effective treatment for the long segment defect of the digital nerve and recipient area with poor blood supply, so the best way of nerve healing can be achieved. In this procedure, the two DMNs are retained in the flap, and vascularized by the accompanying DMA and its branches. The distal cutaneous branches of the two DMNs have sufficient length for dissection and anastomosis with the appropriate PDNs without tension.

We recommend the following steps to achieve the expected surgical outcomes: 1) Preoperatively, we need to determine whether the patient with acute destructive injury or chronic long finger amputation has the desire to reconstruct the index and/or middle fingers, and shows an unwillingness to damage the toes to reconstruct the fingers or a dissatisfaction with a prosthetic finger sleeve. 2) Care should be taken in female patients with substantial subcutaneous fat on the dorsum of the hand because the repaired fingers can appear fatty (Figure 2). 3) Surgeons need to operate noninvasively and carefully protect the DMA. Care should be taken not to compress tissues and create tension in the pedicle throughout its course in the open tunnel before reaching the receipt site. 4) The two DMAs on both sides of the injured long finger were used as the axis to design the flap. The rotation point was 1.5 cm away from the edge of the finger webs. When the island flap was separated and reversed 180° coronally to cover the defective area, the rotation points of the two DMAs formed an arch with the proximal end of the rotated DMAF. After rotation to the palmar side, when the arch formed is transferred to the

palmar side of the finger, the abandoned phalangeal joints and tendon grafts were used to reconstruct the completed amputated phalanges and tendons, then the flap was wrapped and sutured on the dorsal side of the reconstructed finger. In this case, there is no need for sagittal cross transposition of both pedicles of the island flap (e.g., when the long finger is completely amputated at the proximal finger crease, the long finger can be reconstructed). On the contrary, when the formed arch was transferred 180° coronally, it could not reach the palmar side of the finger because the stump of the severed finger blocked it (Figure 1 C). Therefore, in this case, according to Figure 1, the flap was rotated 180° on the coronal plane and then 180° on the sagittal plane before suturing to reconstruct the finger (e.g., when the long finger is completely amputated at the PIP crease or long finger degloving injury).

These procedures display the following advantages. 1) As a result of using the abandoned phalangeal joints and tendon grafts from the severed finger, emergency finger restoration and reconstruction within 8 hours are possible, which are easy and safe, have a high success rate, and have a shortened recovery period. 2) The procedure provides a novel treatment option to repair and reconstruct a degloving injury distal to the palmar digital crease. The two adjacent DMAs can then provide adequate retrograde blood supply to the reverse-island flap and DMNs ensuring an extended flap with a maximal area of 9 × 8 cm^2. 3) It is our intention to follow current microsurgical flap transplantation principles, which include choosing simple and time-saving surgical procedures, avoiding significant damage to non-functional areas as donor sites, and choosing a procedure requiring minimal vascular anastomosis.[28]

The limitations to our procedures were 1) the teardrop-shaped linear scar left in the dorsal side of the hand and a partially injured DMNs. In the event that patients worry about the sequelae of skin grafting at the back of the hand, a variety of perforator flaps can be considered for donor

site restoration. 2) More clinical experience is needed to observe the functional outcomes of finger reconstruction with autologous phalangeal joints and tendon grafts. 3) Many patients had a poor economic status and could not afford formal follow-up visits, secondary surgery, rehabilitation, or secondary tendon release.

In summary, we used an expanded reverse-island flap with two DMAs and DMNs to repair severe index- and middle-finger injuries. Future anatomical studies and long-term postoperative function evaluations are warranted.

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Ethical Approval

The study protocol was approved by our hospitalôs Ethics Committee.

Conflict of interest statement

None.

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Table 1 Characteristics and outcomes of the patients.

Case	Age (year)/ sex	Type of injury	Injured finger	Duration of injury (hours)	Flap size (cm×cm)	DMA Pedicle of the flap	Finger Reconstruction Graft	Outcomes Results and complications	Follow up (months)
1	19/M	Crush-Avulsion	R 2,3	4	9 × 7	1DMA 2DMA	None	The flap survived. The second day after the degloving injury of the right middle finger, the cross-arm operation of the medial skin tube of the left	20

								upper arm was performed,	
2	40/F	Crushed amputation	R 2	4	8 × 8	1DMA 2DMA	Abandoned phalangeal joints and tendon grafts	The flap survived, and the reconstructed index finger was hypertrophic;	23
3	47/M	Crushed amputation	L 2	2	8 × 8	1DMA 2DMA	Abandoned phalangeal joints and tendon grafts	The flap survived with a few tension blisters at the distal end of the flap,	19

4	20/F	Crush completed amputation	L 2,3,4, 5	4	8 × 8	1DMA 2DMA	Abandoned phalangeal joints and tendon grafts	The flap survived with a few tension blisters at the distal end of the flap,	12
5	30/M	Crush completed amputation	R 2,3,4, 5	4	9× 8	2DMA 3DMA	Abandoned phalangeal joints and tendon grafts	The distal end of the flap was 0.5 Ĭ 0.5 cm^2 necrosis, secondary debridement, and suture,	20
6	43/F	Crush-Avulsion	L 2	2	8 × 6	1DMA 2DM	None	The flap survived,	20

						A			
7	21/M	Crush completed amputation	L 3	2	9 × 8	2DMA 3DMA	Abandoned phalangeal joints and tendon grafts	The flap survived.	21
8	20/M	81 hours after finger amputation	L 2	81	8 × 8	1DMA 2DMA	Free iliac bone graft	The flap survived.	20
9	17/M	Crush completed amputation	R 2	4	8 × 8	1DMA 2DMA	Abandoned phalangeal joints and tendon grafts	The flap survived with a few tension blisters at the distal end of the flap,	18
10	20/M	Crush completed	L 2	2	8 × 6	1DMA 2DM	Abandoned phalangeal joints and	The flap survived,	20

	amputati on	A	tendon grafts

L, left; R, right; DMA, dorsal metacarpal artery.

Table 2. Clinical results

Case	Reconstructed finger	The extent of the amputation stump (defined by finger segments)		S2PD, (mm)	ROM of MCP (°)		ROM of PIP (°)		Postoperative sensory recoveries		Modified hand function impairment score (P=0.002 *)	
		Preoperative	Postoperative		IS	OS	IS	OS		Preoperative		Postoperative
1	R2	Midpoint of PPS	Distal 1/3 of DPS	5	75	79	20-50	103	S4	95.7		65.9
2	R2	Distal 1/3 of PPS	Distal 1/3 of DPS	5	73	82	21-50	109	S4	91.5		82
3	L2	Distal 1/3 of PPS	Distal 1/3 of DPS	7	72	76	21-47	108	S3	88.4		52.6
4	L2	Distal 1/3 of PPS	Distal 1/3 of DPS	10	59	80	23-43	106	S2	92.5		58.2
5	L3	Proximal 1/4 of	Proximal 1/3 of	7	70	80	21-48	110	S3	92.3		38.3

		PPS	DPS								
6	L2	Distal 1/4 of PPS	Distal 1/3 of DPS	5	72	82	23-47	109	S4	92.5	42.2
7	L3	Proximal 1/4 of PPS	Distal 1/3 of DPS	5	71	80	21-46	108	S4	87.9	48.3
8	L2	Proximal 1/3 of MPS	Distal 1/3 of DPS	5	68	78	23-48	105	S4	97.9	63.9
9	R2	Distal 1/3 of PPS	Distal 1/3 of DPS	8	67	81	21-47	108	S3	91.5	56.1
10	R2	Proximal 1/3 of MPS	Distal 1/3 of DPS	5	62	79	22-48	110	S4	88.4	51.9
Mean				6.2 ± 1.75	68.9 ± 5.04	79.7 ± 1.83	21.6 ± 1.07-47.4 ± 2.0	107.6 ± 2.27	-	91.92**	52.28**

1

S2PD, static 2-point discrimination. ROM, range of motion; PIP, proximal interphalangeal joint; MCP, metacarpalphalangeal joint; PPS, proximal phalange segment; MPS, middle phalange segment; DPS, distal phalange segment, L, left; R, right.

*P-value is calculated by Wilcoxon signed rank-sum test.

** Median.

Figure legends

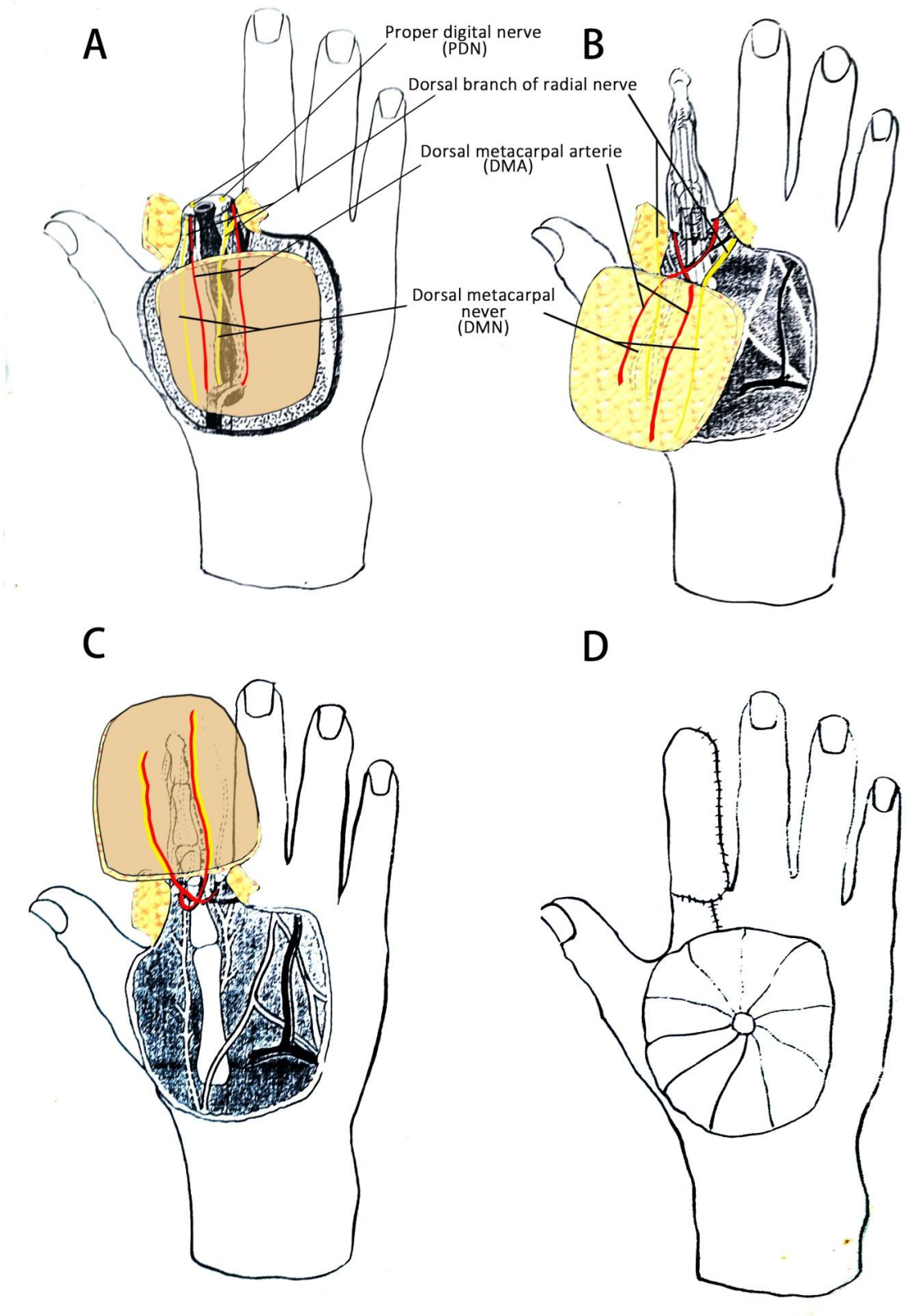
Figure 1 Right index-finger injury. Schematic diagram shows the steps in the finger reconstruction. (A) A reverse-island flap was created from the dorsal side of the wrist and hand, with two adjacent DMAs and the DMNs obtained between the 1ï2 and 2ï3 metacarpals. (B) Finger reconstruction using the abandoned phalangeal joints and tendon grafts from the severed finger when necessary. (C) Flap transplantation. (D) Reconstructed index finger and repaired donor site.

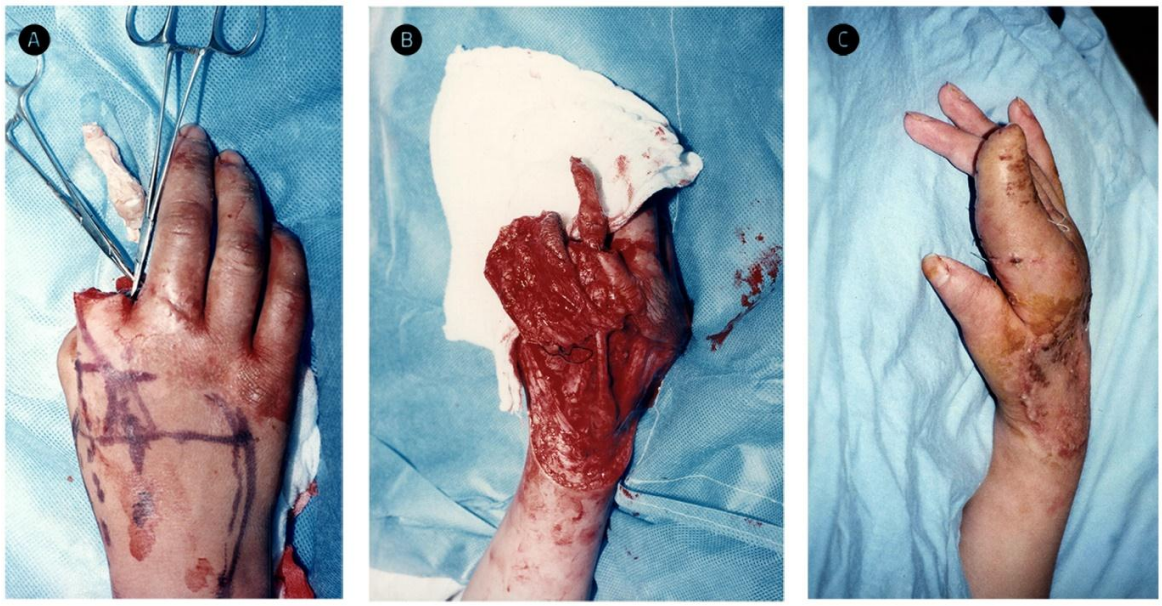
Figure 2 Right index-finger amputation. (A) Amputated right index finger. (B) Creation of a reverse-island flap from the dorsal sides of the wrist and hand, with two adjacent DMAs and the DMNs obtained from the 1ï2 and 2ï3 metacarpals. (C) The reconstructed finger appears fatty.

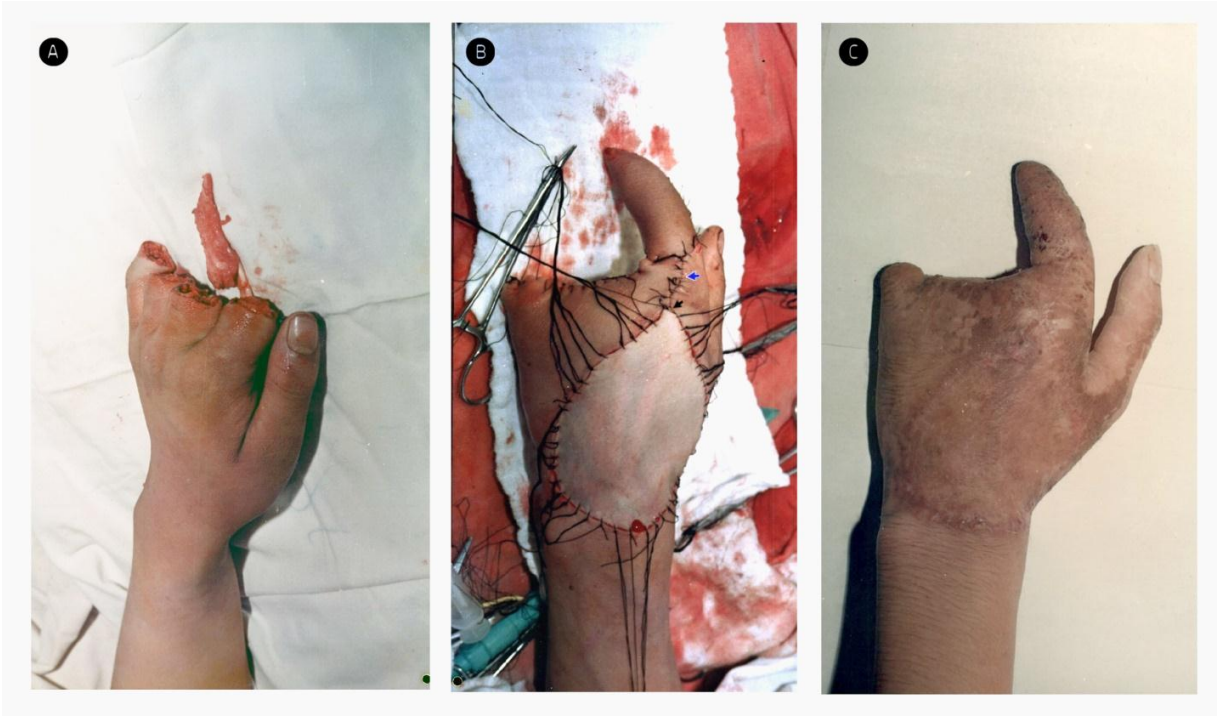
Figure 3 Left two to five finger destructive crush injury with complete amputation. (A) left 3,4,5 fingers amputation. Left index finger was reconstructed by a reverse-island flap from the dorsal sides of the wrist and hand, with two adjacent DMAs and DMNs obtained between the 1ï2 and 2ï3 metacarpals. (B) Finger reconstructed using the abandoned phalangeal joints and tendon grafts from the severed finger. Black arrow showing the teardrop-shaped flap. Blue arrow showing the incision was extended distally along the longitudinal axis. (C) The reconstructed finger.

Figure 4 Complete amputation of the proximal segment of the left index finger - incomplete

amputation of fingers 2-5. (A) Left index finger complete amputation. (B) Left index finger was reconstructed by abandoned phalangeal joints and tendon grafts and a reverse-island flap from the dorsal sides of the wrist and hand, with two adjacent DMAs and the DMNs obtained between the 1ï2 and 2ï3 metacarpals. The abandoned phalangeal joints and tendon grafts was from the severed finger. (C) Reconstructed left index finger.


A
Proper digital nerve
(PDN)
Dorsal branch of radial nerve
Dorsal metacarpal arterie
(DMA)
Dorsal metacarpal
never
(DMN)
B
C
D


A
B
C


A
B
C