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ORIGINAL RESEARCH

Similar Diameter of Cutaneous Branches of the Proper Digital Nerve and Stump of the Proper Palmar Digital Nerve was a Key Factor for the Sensory Reconstruction in Short Term Outcome of Finger Pulp Defects: A Retrospective Study

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Introduction: Whether an innervated reverse digital artery island flap is superior remains controversial. To date, no thorough investigation has been undertaken regarding the exact factors underlying this phenomenon. We aim to systematically summarize the innervated reverse digital artery island flap by leveraging our dataset and extract the key contributing factors.

Materials and Methods: A total of 79 patients from June 2016 to September 2019 who underwent innervated reverse digital artery island flap were evaluated retrospectively. Thirty nine underwent sensory nerve reconstruction with similar diameter of cutaneous branches of the proper digital nerve and stump of the proper palmar digital nerve (S-innervated group), while 40 with different diameter (D-innervated group). Sensory function was assessed by static two-point discrimination and the modified sensory evaluation standard of British Medical Research Council. Motor function was assessed by the total activity measurement. Pigmentation of the flap was also evaluated by Taylor hyperpigmentation scale. Seventy who underwent non-innervated reverse digital artery island flap at the same period was considered as the control group.

Results: All 149 flaps survived completely. There was significant difference in age, operation time, time from injury to surgery, s2PD of the flap within 1 year and pigmentation between S-innervated group and Non-innervated group, while operation time and s2PD of the flap within 1 year between D-innervated group and Non-innervated group.

Conclusion: The nerve diameter matching was a critical factor in innervated reverse digital artery island flap in the early restoration of sensory function and pigmentation. A significant discrepancy in nerve diameters not only compromised the intended therapeutic outcomes but also increased the incidence of neuroma formation.

Keywords: digital artery flap, innervated flap, sensory function, nerve diameter matching, pigmentation

Introduction

The hand, an indispensable instrument of human endeavor, stands as the very embodiment of labor. To meet its intricate functional demands, the skin on the pads of the fingers is not merely thick, tough, or elastic; it is a marvel of nature that is exquisitely adaptable to withstand the rigors of daily toil while retaining remarkable flexibility.[1] The fingertip, a vital anatomical structure responsible for interfacing with the external environment, plays an indispensable role in maintaining the integrity of fine motor functions such as grasping, tactile sensation, and precise manipulation.[2]

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Fingertip or pulp soft tissue defects represent one of the most frequent hand injuries encountered in clinical practice and necessitate prompt and effective reconstruction and repair. These injuries typically occur in the distal portions of the fingers, particularly in the fingertip region, leading to significant functional impairment and considerable disruption of patients' daily activities and occupational performance.[3] Over the past two decades, the reverse island flap based on the digital artery has emerged as one of the most commonly used technique for reconstructing finger pulp defects, yielding remarkable and consistently commendable outcomes.[4] As medical technology advances and surgical techniques continue to be refined, achieving a lifelike appearance and superior sensory recovery have become the twin pillars of excellence in finger pulp defect reconstruction.[5] Therefore, flaps incorporating nerve branches have also received considerable attention due to their superior sensory recovery, achieving consistently satisfactory outcomes.[6–8] However, several studies have indicated that the anastomosis of nerves for the flap does not significantly affect sensory recovery outcomes.[9–11] In a prior small-sample study conducted by our team, skin flaps incorporating nerve branch anastomosis demonstrated a significantly greater advantage in terms of sensory function recovery than those without nerve branch anastomosis.[3] However, certain individuals hold contrasting perspectives regarding this issue.[12]

As is widely recognized, the quality of nerve anastomosis is significantly correlated with sensory recovery in the flap. Neuroanastomosis is influenced by a variety of factors, including the site of injury, the diameter of the nerve stumps, and the technique used by the surgeon performing the anastomosis. The epineural suture technique is the most widely used method for nerve repair in clinical practice. We expanded the sample size of the study and conducted an analysis of flaps incorporating nerve branch anastomosis. The findings indicated that the thickness of the nerve branches served as a more critical determinant in influencing sensory recovery outcomes. To date, no studies have systematically analyzed matching accuracy at the suture site of nerve endings. Consequently, we conducted a retrospective analysis of various data related to suture techniques for nerve stumps with different diameters of the palmar cutaneous branch of the proper digital nerve on the reverse digital artery island flap in the treatment of finger pulp defects. We aimed to identify a key determinant influencing sensory recovery in flaps and provide a scientific foundation and reference for future clinical practice.

Materials and Methods

This study retrospectively reviewed the medical records of patients who underwent surgical intervention for single fingertip or pulp soft tissue defects of the index, middle, ring or little finger with exposure of the distal phalanx who did undergo suturing of the palmar cutaneous branch of the proper digital from June 2016 to September 2019 identified using our hospital's medical records system. Additionally, the patients for whom follow-up data were available for more than five years were included. The exclusion criteria were: 1) injuries to the thumb; 2) neurological diseases that would affect the follow-up date; 3) concomitant injuries that significantly impaired postoperative rehabilitation; and 4) loss to follow-up or incomplete medical records. This report conforms to the World Medical Association Declaration of Helsinki and subsequent amendments. This study was approved by our institutional ethics committee (2023ky194), and informed consent was obtained from the patients.

Surgical Technique

The surgical procedure was performed under brachial plexus nerve block anesthesia, and an upper arm pneumatic tourniquet was used for optimal hemostasis and visualization. Before the operation, the Allen test was conducted to assess the patency of the proper digital arteries on both sides of the injured finger. Routine debridement was performed to remove the contaminated particles and nonviable tissue debris. For the index finger, the ulnar side was selected; for the little finger, the radial side was chosen; for the middle and ring fingers, the flap was harvested on the more injured side.

All procedures were conducted by a single senior surgeon. The revised digital artery flaps were harvested using the method described by Muneuchi et al.[13] In the innervated group, following the design of the flap, the dissection was conducted in a proximal-to-distal direction until an adequate pedicle length was achieved, typically corresponding to the level of the distal interphalangeal (DIP) joint. During this procedure, the proper palmar digital nerve and vascular bundle were meticulously exposed. Typically, 1 to 4 cutaneous branches of the proper palmar digital nerve extended toward the flap. One or more suitable cutaneous branches for unilateral neurorrhaphy, rather than all of them, were selectively harvested. The proper palmar digital artery was ligated proximally. The pedicle was elevated, incorporating the digital artery, selected cutaneous branches of the nerve,

and perivascular soft tissue, while preserving the stump of the proper palmar digital nerve. Upon elevating the island flap, it was rotated into the defect. The harvested cutaneous branches were subsequently meticulously sutured to the stump of the proper palmar digital nerve on the more injured side under loupe magnification using epineural suture, regardless of the diameter. The flap was loosely sutured to prevent compression of the pedicle, and the donor site was repaired using full-thickness skin grafts (Figure 1a–d). During the operation, there were two situations regarding the diameter of the anastomosed nerves: matching and nonmatching.

Postoperative Management

The perfusion of the transferred tissue was meticulously monitored through a triad of vital indicators: color, capillary refill, and temperature. Patients were administered broad-spectrum antibiotics for 48 hours, and painkillers were used if necessary. The compression bandage over the skin graft was removed 7 days postoperatively, and the sutures were removed 14 days postoperatively. Hand function exercises were commenced under the guidance of a certified rehabilitation therapist 3 weeks postoperatively.

Outcome Evaluations

We collected and analyzed the postoperative data of the static two-point discrimination (s2PD) of the flaps. The total activity measurement (TAM), which measures the limitations of the range of motion (ROM) of the metacarpophalangeal and interphalangeal joints, was also evaluated. At the 5-year postoperative follow-up, to assess whether a significant pigmentation difference exists, we compared the pigmentation levels of the skin surrounding the donor site with those of the flap itself by Taylor hyperpigmentation scale.[14] The British Medical Research Council's (BMRC) sensory evaluation standard (S0-S4) were also evaluated. Data regarding sensory function were obtained by a surgeon who was not involved in the overall treatment process. The s2PD was measured at both the ulnar and radial sides of the flap, and the mean s2PD was recorded. The factor of diameter matching at the nerve anastomosis sites during surgery was also analyzed. We defined cases with a nerve end diameter difference exceeding 50% as the different innervated group (d-innervated group) and all other cases as the similar innervated group (s-innervated group). The non-innervated reverse digital artery island flap who underwent at the same period was considered as the control group.

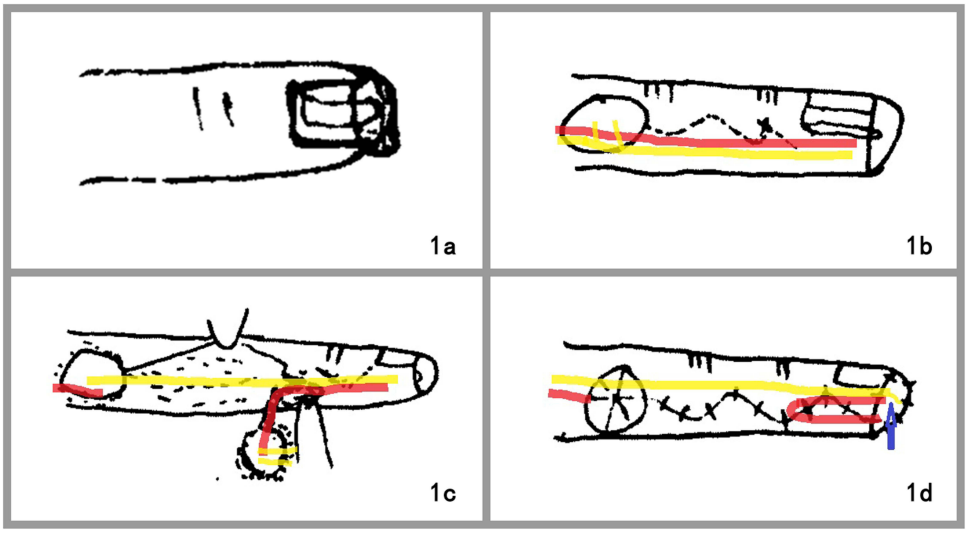

Figure 1 Schematic diagram of the innervated reverse digital artery island flap. (**a**) Injury of the fingertip and pulp. (**b**) The design of the innervated reverse digital artery island flap, the yellow lines represent the nerves and their branches, the red lines represent the artery. (**c**) The site of flap excision. (**d**) Harvesting of the flap, the blue arrow mean the indicated the anastomosis of the nerve.

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Statistics

The statistical analysis was conducted using SPSS 23.0 software. The measurement data are presented as the means ± standard deviations, whereas the categorical data are presented as percentages. For d-innervated group and s-innervated group Chi-square tests were used to compare variables such as sex, affected side, dominant hand, and functional evaluation. T tests were used to compare the remaining data. For d-innervated group or s-innervated group, compared with non-innervated group (control group), Welch's ANOVA test were used to compare variables such as sex, affected side, dominant hand, and functional evaluation, Welch's *t* test were used to compare the remaining data. A P value of <0.05 was considered statistically significant.

Results

Among the innervated group, 39 patients exhibited similar nerve stump diameters (s-innervated group), whereas 40 patients demonstrated marked differences in diameter (d-innervated group), and 70 patients were in the noninnervated group (control group). All 149 flaps survived completely. The demographic and clinical characteristics of the three studied groups are summarized in Table 1. There were no significant differences among the three groups with respect to sex, injured side, or injured finger. There were significant differences in age, operation time and time from injury to surgery between the s-innervated group and the noninnervated group and significant differences in operation time between the d-innervated group and the noninnervated group. When nerve anastomosis was performed during flap surgery, the operative duration was significantly greater than that of flap surgery without nerve anastomosis.

Six patients in the noninnervated group experienced complications, including transient venous congestion (3 patients), infection (3 patients), and moderate pain (2 patients). In contrast, two patients in the s-innervated group experienced complications, including infection (3 patients) and moderate pain (1 patient), and five patients in the d-innervated group experienced complications, including moderate pain (5 patients). The data are shown in Table 2. However, five patients in the d-innervated group who experienced moderate pain underwent secondary surgical intervention due to neuroma formation.

The s2PD in the s-innervated group was significantly different from that in the other two groups within one year postoperatively. However, as time progressed, no significant differences were observed among the three groups. Furthermore, no significant differences in TAM were observed among the three groups. At the 5-year postoperative

Table 1 Demographic and Clinical Characteristics

	S-Innervated Group (A)	D-Innervated Group (B)	Non-Innervated Group (C)	P value
Age (year)	51.3±10.6	53.2±8.7	56.4±7.9	P(A&C)<0.05
Sex				
Male	14	19	28	0.410
Female	25	21	32	
Injured finger				
Index	5	6	9	0.660
Middle	12	15	20	
Ring	14	8	26	
Little	8	11	15	
Surgery side				
Left	11	12	22	0.803
Right	28	28	48	
Size of flap (cm^2)	4.2±0.94	4.4±0.74	4.1±1.2	-
Operation time(min)	73.4±7.6	70.6±8.8	54±9.4	P(A&C), P(B&C)<0.05
Time from injury to surgery (hour)	71.5±8.6	73.6±14.8	78.3±17.4	P(A&C)<0.05
Follow-up time (month)	68.2±3.4	68.4±5.1	67.9±4.1	-

Table 2 Comparison of Operative Complications

Complications	S-Innervated Group (A)	D-Innervated Group (B)	Non-Innervated Group (C)	P value
Venous congestion	0	0	3	
Infection	3	0	3	
Moderate pain	1	5	2	
Total	4	5	8	0.947

follow-up, all patients had achieved S3+ sensory recovery. Compared with those in the other two groups, the flap appearance in the s-innervated group demonstrated superior recovery. The data are shown in Table 3.

Case 1

A 56-year-old female patient, who was admitted to the hospital 6 h after tissue defects caused by machine impact. Emergency debridement was performed and the size of defect of the right index finger was 1.4×1.8 cm.Then, the patient underwent a secondary operation of innervated reverse digital artery island flap. The nerve end diameter was same (s-innervated group) (Figure 2).

Case 2

A 39-year-old female patient, who was admitted to the hospital 2 h after tissue defects caused by traffic accident. Emergency debridement was performed and the size of defect of the right index finger was 0.9×1.2 cm.Then, the patient underwent a secondary operation of innervated reverse digital artery island flap. The nerve end diameter was different (d-innervated group) (Figure 3).

Discussion

Fingertip defects are among the most common types of trauma encountered in emergency departments. These injuries can result from various causes, including accidental cuts, crushing, abrasions, and burns, leading to varying degrees of pain and functional impairment in patients.[15] For superficial injuries, satisfactory outcomes can be achieved through self-administered wound care and secondary healing. When the defect area of the finger pulp is extensive and the phalanx is exposed, secondary healing can achieve wound closure, although the resulting scar pain following wound healing significantly impairs finger function.[16] In 1985, Glicenstein first described a reverse digital artery island flap, which was particularly suitable for reconstructing a plump finger pulp.[17] The reverse digital artery flap subsequently gained

Table 3 The Follow-up Outcomes of the Patients

	S-Innervated Group (A)	D-Innervated Group (B)	Non-Innervated Group (C)	P value
s2PD of the flap (mm)				
6 months after surgery	12±2.1	17.4±2.6	18.5±3.6	P(A&B), P(A&C)<0.05
1 year after surgery	7.6±2.4	10.4±2.7	10.8±1.6	P(A&B), P(A&C)<0.05
2 years after surgery	7.3±1.7	7.5±2.2	7.6±1.9	-
5 years after surgery	6.9±1.9	7.2±2.7	7.4±1.3	-
TAM (degree)				
3 months after surgery	227±18	232±23	223±46	-
6 months after surgery	247±27	252±37	248±38	-
1 years after surgery	247±18	240±33	252±36	-
2 years after surgery	250±18	245±44	247±29	-
5 years after surgery	257±42	263±29	259±18	-
BMRC sensory evaluation at 5 years after surgery				
S3+	39	40	70	-
Taylor hyperpigmentation scale at 5 years after surgery	3.6±1.3	5.2±2.4	5.8±2.7	P(A&B), P(A&C)<0.05

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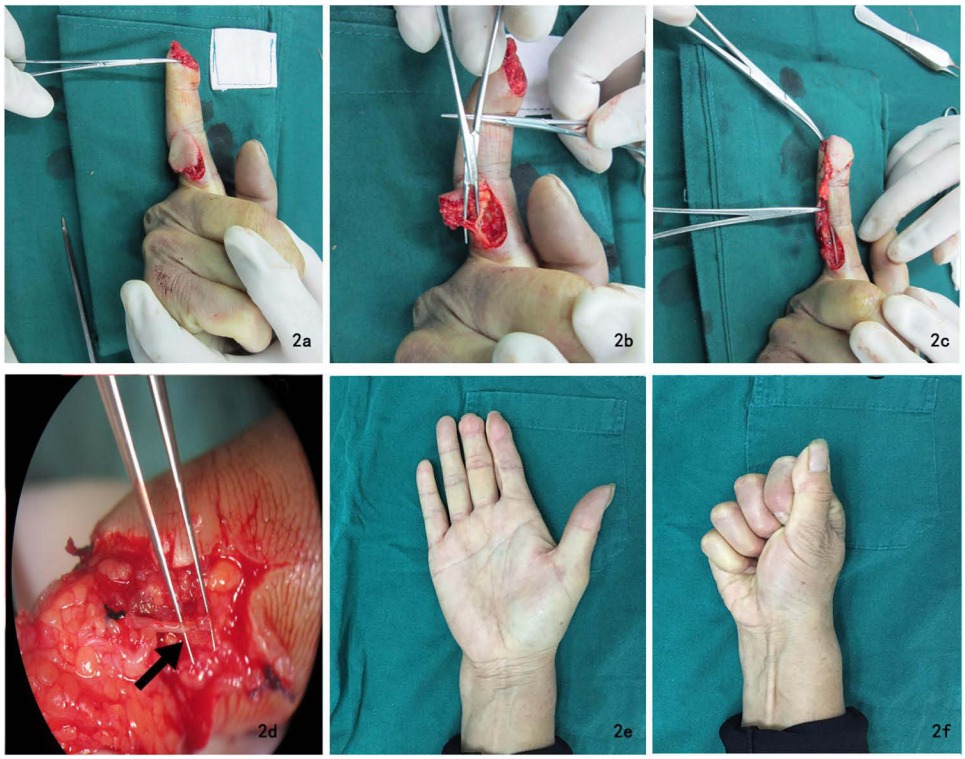

Figure 2 Innervated reverse digital artery island flap of the s-innervated group. (**a**) Harvesting the flap on the ulnar side for covering the defect in the distal interphalangeal area of index fingers of a 56-year-old female patient. (**b**) Dissection of the two cutaneous branches of the digital nerve. (**c**) Rotation of the flap. (**d**) the black arrow indicated the neural anastomosis site of the flap, the diameter of the nerve anastomosis was similar. (**e** and **f**) Aesthetic appearance and function at the 60-month follow-up visit.

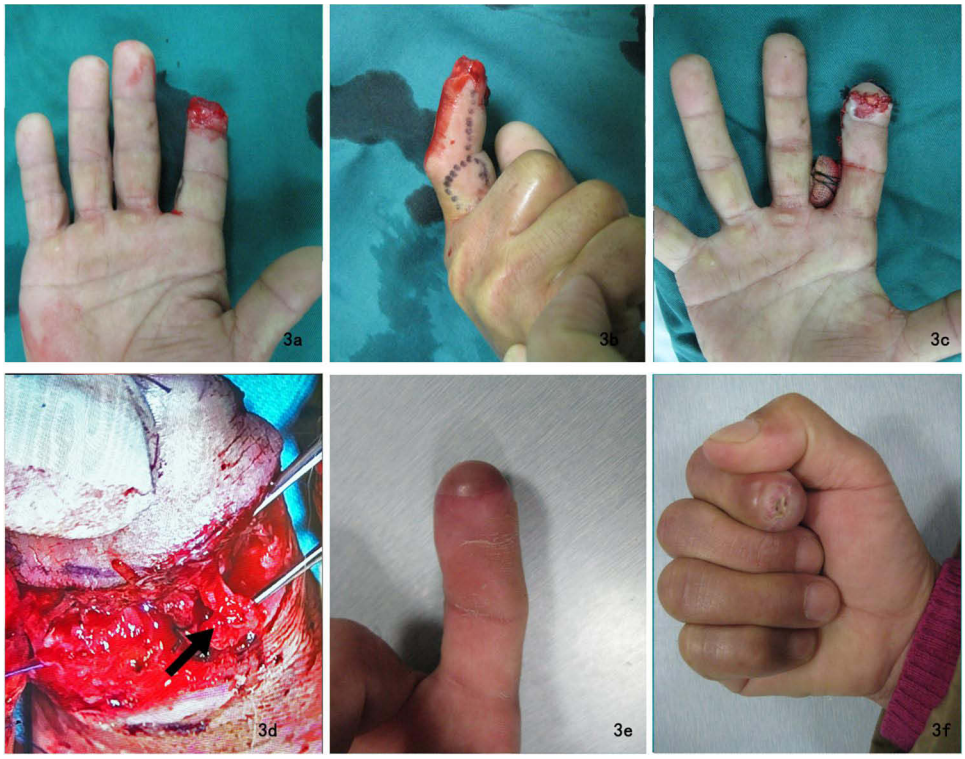

Figure 3 Innervated reverse digital artery island flap of the d-innervated group. (**a**) Defect in the distal interphalangeal area of index fingers of a 39-year-old female patient. (**b**) The site of flap design. (**c**) Harvesting the flap on the ulnar side of the index finger. (**d**) the black arrow indicated the neural anastomosis site of the flap, the diameter of the nerve anastomosis was different. (**e** and **f**) Aesthetic appearance and function at the 60-month follow-up visit.

popularity in hand surgery for fingertip reconstruction. This single-stage procedure is characterized by its simplicity and low complication rate. In clinical applications, this flap has demonstrated reliability and durability over time. With the continuous advancement of microsurgical techniques, the great toe fibular flap has gradually demonstrated a trend toward replacing the reverse digital artery island flap for finger pulp reconstruction due to its superior incision concealment in recent years.[18] However, due to the relative simplicity of the procedure and the lower technical demands associated with digital artery flaps, they remain widely utilized in clinical practice.

In recent years, increasing emphasis has been placed not only on the aesthetic outcomes of flaps but also on the postoperative recovery of sensation. In 1993, Lai et al proposed the use of an innervated reverse digital artery flap to achieve more satisfactory reconstruction of the sensate pulp.[19] They utilized the dorsal branches of the proper digital nerve and the superficial sensory branches of the digital nerve for bilateral neurorrhaphy. While this approach yielded an ideal sensory outcome in the repair area, it also resulted in significant sensory loss on the dorsal side of the proximal and middle phalanges. To avoid this limitation, some surgeons have proposed sensory reconstruction through bilateral neurorrhaphy using small branches of the proper digital nerve to directly innervate the donor flap. However, due to the variability in the number, distribution, and length of digital nerve branches during flap excision, this introduces significant challenges for bilateral nerve anastomosis. Therefore, we used the unilateral nerve suture technique and achieved highly satisfactory outcomes.[3]

A previous study indicated that the smaller branches of the proper digital nerve exhibited anatomical consistency during the procedures.[20] They reported that, on average, there were 2.7 nerve branches at the proximal level, with the majority distributed at the level of the proximal one-third of the proximal phalanx. These areas corresponded precisely to the locations of the flap donor sites. This finding was consistent with our observations during the flap excision process, where we identified 1 to 4 nerve branches. Kim also noted that the distal interphalangeal joint level presents a greater number of digital nerve branches, with greater anatomical variability.[21] This finding indicated that following finger injury, the diameter of the nerve stump at the wound site exhibited significant variability, introducing uncertainty in the selection and execution of surgical repair and suture techniques. This also accounts for the observed variability in the diameter of the suture ends.

Our follow-up data revealed that the anastomosis of nerve stumps with similar diameters played a critical role in the early restoration of sensory function in the flap group compared with the noninnervated group. These findings indicate that flaps with anastomosed nerves exhibit a significant advantage in the early restoration of sensory function. However, no advantage in sensory recovery was observed within 1 year in patients with a significant difference between the diameters of the nerve anastomosis ends. The anastomosed nerves played a critical role in sensory reconstruction during the early phase of sensory function recovery in the flap. When there is a mismatch in nerve diameter, nerve anastomosis may not yield effective results and is likely to lead to the formation of a neuroma.[22] This finding further supported the conclusion that s-innervated group exhibited significantly better sensory recovery outcomes following flap reconstruction when compared to d-innervated group within one-year postoperative follow-up period. Over time, nerve fibers from the severed ends of the digital nerve and its branches progressively infiltrate the flap, leading to partial restoration of sensation.[23] This may explain why the sensory function of the flap gradually recovers over time despite the absence of nerve anastomosis. Our findings suggested that, despite the relatively slow infiltration of sensory fibers, this regenerative mechanism serves as the primary driver of sensory recovery in skin flaps, with its impact significantly surpassing that of the nerve anastomosis. Similarly, neural innervation exerts a substantial influence on hyperpigmentation in skin and soft tissues. Following denervation, skin and soft tissues become highly susceptible to developing pigmentation changes within several months.[24] This observation also supported, from an alternative perspective, that in the surgical diagram, the s-innervated group exhibited normal pigmentation during the 15-month postoperative follow-up, whereas the d-innervated group and control group developed hyperpigmentation. At the postoperative follow-up time points, the finger movement function in each group remained unaffected. This finding suggests that the surgical technique was well established and that harvesting the common digital nerve branches and performing nerve anastomosis did not compromise functional outcomes.

This study had several limitations. First, the sample size was relatively small. To account for potential biases and confounding factors, a larger sample size is necessary for a more comprehensive analysis. Second, this was a retrospective study, which limits the strength of our findings.

In conclusion, the anastomosis of the palmar cutaneous branches of the proper digital nerve with the stump of the proper palmar digital nerve plays a critical role in the early restoration of sensory function in the flap and pigmentation. Nerve diameter matching is a critical factor. A significant discrepancy in nerve diameter not only compromises the intended therapeutic outcomes but may also increase the incidence of neuroma formation.

Abbreviations

DIP, distal interphalangeal; s2PD, static two-point discrimination; TAM, total activity measurement; BMRC, British Medical Research Council.

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Disclosure

The authors report no conflicts of interest in this work.

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