Heterotopic Digital Replantation in Mutilating Hand Injuries: An Algorithmic Approach Based on 53 Cases and Literature Review

Tommy Nai-Jen Chang, MD[1] Chung-Chen Hsu, MD[1] Hywel Dafydd, MD[1] Neil S. Sachanandani, MD[1] Lisa Wen-Yu Chen, MD[1] Yi-Chieh Chen, MD[1] Yu-Te Lin, MD FACS[1] Chih-Hung Lin, MD[1] Cheng-Hung Lin, MD, MBA, FACS[1]

[1] Department of Plastic and Reconstructive Surgery, Chang Gung Memorial Hospital, Chang Gung Medical College and Chang Gung University, Taoyuan, Taiwan

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Address for correspondence Cheng-Hung Lin, MD, MBA, FACS, Department of Plastic and Reconstructive Surgery, Chang Gung Memorial Hospital, Chang Gung University, 5, Fu-Hsing St. Kuei-Shan, Taoyuan, Taiwan (e-mail: lukechlin@gmail.com).

Abstract

Background Reconstruction of the mutilated hand is one of the most difficult challenges for hand microsurgeons. When multiple digits are amputated, orthotopic digital replantation of the available remnants may not adequately restore the hand function. In such cases, heterotopic digital replantation may provide a more functional reconstruction.

Methods Between 1997 and 2018, 53 patients with mutilating hand injuries were treated with heterotopic digital replantation at our institution. A retrospective chart review was conducted to determine the details of the injury, indications for heterotopic digital replantation, and functional outcomes.

Results In total, 173 digits were amputated from 53 patients (one patient suffered from bilateral hand injuries, so totally 54 hands). Sixty-eight digits underwent heterotopic digital replantation, 30 digits had orthotopic digital replantation, and 75 stumps were terminalized. The survival rate of digits treated by heterotopic digital replantation and orthotopic digital replantation was 83.8% (57/68) and 86.7% (26/30), respectively ($p = 1$). Tripod grip was achieved in 83.3% (45/54) of patients following replantation and optional secondary reconstructive surgeries.

Conclusion Heterotopic digital replantation is a practical and reliable method for achieving optimal hand function following mutilating hand injuries. The basic principles are to restore a functional thumb in the first instance, followed by at least two adjacent fingers against which the thumb can oppose. This method is particularly indicated when orthotopic digital replantation of the available amputated parts would yield a suboptimal result.

Keywords
- heterotopic digital replantation
- spare parts surgery
- mutilating hand injury
- thumb reconstruction

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Reconstruction of the mutilated hand is one of the most difficult challenges for hand microsurgeons.[1] Replantation of amputated digits is without doubt the best option to restore function, especially when multiple digits are involved.[2] Refinements in microsurgical technique and effective postoperative monitoring have caused the survival rate of digital replantation to approach 90%.[3–5] However, the challenge is not only to restore circulation to a digit, but also to create a functional hand. To this end, restoration of an opposable thumb and at least two fingers to work against, each pain-free and sensate with mobile and stable joints, is the key priority when treating a mutilated hand.[6,7]

Orthotopic digital replantation (ODR) restores amputated digits in their original anatomical positions. This is the most straightforward and established procedure following digital amputation. However, ODR cannot be performed for cases where amputated parts or their recipient stumps are unsalvageable or unavailable. In such circumstances, heterotopic digital replantation (HDR), temporary ectopic implantation, or toe-to-hand transfer should be considered.[8–16] HDR is defined as replacing an amputated digit in a position other than its original anatomical site. As opposed to ODR, HDR is a functional approach to reconstruction rather than anatomical approach to reconstruction. In most clinical scenario the donor site is from the ipsilateral hand, but in the extremely rare situations, the donor site can be from contralateral side.[17] Another purported advantage of HDR is the limitation of donor site morbidity to the zone of trauma.[15] Despite these reported advantages, the optimal strategy of replantation in terms of where to positioning the amputated digits remains a topic for debate.[8,10,18]

In this article, we retrospectively analyzed our HDR experience of 53 mutilated hands in our hospital, between 1997 and 2018. The clinical results of our reconstructions are presented and used as a basis for an algorithm for the management of mutilating hand injuries with HDR.

Methods

Between 1997 and 2018, 53 patients with mutilating hand injuries received emergent HDR at Chang Gung Memorial Hospital in Linkou, Taiwan. All the patients were admitted from the emergency department and evaluated by the duty plastic and reconstructive surgeons. If the general condition was stable, the patients received immediate reconstruction. After the microsurgical reconstruction, the patients were transferred to a highly specialized microsurgical intensive care unit (ICU) for postoperative care and the circulation of the replanted digits were monitoring within 3 to 7 days. The monitoring was performed using clinical assessment by doctors and well-trained ICU nurses, laser Doppler imaging, and remote real-time monitoring was also performed periodically via smartphone photography and text communication.[19] The replanted digits' condition were assessed every hour on the first day, every 2 hours from the next day until the patients were transferred to the ordinary ward. Patients with unstable condition were checked every hour during the ICU stay.[20]

A retrospective chart review was undertaken to collect the following data: demographics, mechanism of injury, which digits were amputated, level of amputation, the indications for HDR, associated hand injuries, ancillary procedures, secondary surgeries, and functional outcome. Functional outcome was measured both in terms of survival of the digit and functional pinch status. Fisher's exact test was used to compare the survival of ODR and HDR.

Results

The cohort consisted of 45 male and 8 female patients with a mean age of 36.5 years (ranged from 11 to 75 years old). Note that 98.1% (52/53) cases resulted from industrial accidents, with the other patient following a knife assault. A total of 173 digits were amputated. The initial emergent surgery comprised 68 HDRs (including 5 vascularized joint transfers) and 30 ODRs. Seventy-five digits were terminalized.

The survival rates of HDR and ODR were 83.8% (57/68) and 86.7% (26/30), respectively ($p = 1$) (►**Table 1**). Detailed analysis of the survival rate seen in the HDR group revealed that the success of HDR to a 2nd to 5th fingers was 89.8% (44/49), comparable to the 86.2% (25/29) success rate with ODR. However, a significantly lower survival rate of 68.4% (13/19) was seen with HDR to the thumbs compared to those applied on 2nd to 5th fingers ($p = 0.032$). However, only 66.7% (4/6) patients with a failed thumb HDR chose to proceed with secondary reconstruction using toe-to-thumb transfer.

Table 1 The number of orthotopic and heterotopic digit replantation and the strategies for finger reconstruction

Strategy of HDR	Total number	Success rate (%)
HDR	68	83.8 (57/68)
1A	7	71.4 (5/7)
1B	11	63.6 (7/11)
1C[a]	3	66.7 (2/3)
2A	13	100 (13/13)
2B	15	73.3 (11/15)
2C	2	100 (2/2)
2D	4	100 (4/4)
3A	9	100 (9/9)
3B	3	100 (3/3)
3C	4	75 (3/4)
ODR	30	86.7 (26/30)
SR	75	

Abbreviations: HDR, heterotopic digital replantation; ODR, orthotopic digital replantation; SR, stump revision.

[a]Cases in 1C received immediate opponensplasty for thenar muscle injury from amputated finger's flexor digitorum superficialis, and so the success defined as "the outcome at least achieves pulp pinch"; and these three fingers were not included in the number of HDR because they were not transplanted digits.

Table 2 The distribution of the digit reconstruction during mutilating injury

	Amputated digit	Reconstruct digit (HDR + ODR)	Reconstruct percentage	HDR donor digit	HDR receipt digit
Thumb	22	20[a]	90.9	0	19
Index finger	45	13	28.9	26	8
Middle finger	42	31	73.8	17	21
Ring finger	37	27	73.0	13	17
Little finger	27	7	25.9	12	3

Abbreviations: HDR, heterotopic digital replantation; ODR, orthotopic digital replantation.
[a]Including one pollicization

The index finger was the most common donor for HDR, followed by the middle, ring, and little fingers. The amputated thumbs were never used as HDR donor digits. In terms of recipient digits, the thumb was the most commonly reconstructed digit (86.4% [19/22]) by HDR, followed by the middle finger (50% [21/42]), ring (45.9% [17/37]), index (17.8% [8/45]), and little finger (11.1% [3/27]) (►**Table 2**).

Five immediate vascularized joint transfers were performed to replace destroyed joints. Joint transfers were either pedicle ($n = 1$) or free ($n = 4$) and harvested either from an amputated part ($n = 3$) or the stump ($n = 2$), where they would have otherwise been functionless.

The functional tripod grip (thumb to at least two fingers) was achieved in 83.3% (45/54) hands, and pulp pinch (only thumb to any single finger) was preserved in 9.3% (5/54) hands following the reconstruction. Note that 7.4% (4/54) hands did not achieve any kind of pinch grip. Three of them had failure of the thumb HDR; one patient had successful thumb HDR with the other four digits amputation. This subset of patients refused secondary toe-to-thumb transfer.

The ancillary procedures such as flap reconstruction and tendon transfer were performed relatively frequently to improve hand function (►**Table 3**). Immediate flap reconstructions were performed in 10 patients for soft tissue coverage. The flaps included two free anterolateral thigh flaps, one free fillet flap and three pedicled fillet flaps, two pedicled groin flaps, and two local flaps. Twelve immediate tendon transfers were also performed. Besides, secondary soft tissue reconstructions were performed in 11 patients. These consisted of two anterolateral thigh free flaps, two medial sural artery perforator free flaps, one lateral arm free flap, five pedicled groin flaps, and one cross-finger flap. Eight secondary tendon transfers were required. Five patients underwent secondary toe transfers that included three great toes to thumb, one second toe to thumb, two second toe to middle finger, and one third toe to ring finger transfer (total seven toe-to-hand transfers) (►**Table 4**). The illustrative cases are presented in ►**Figs. 1–3**.

Table 3 Associated surgeries in heterotopic digit replantation

	Immediate surgery	Secondary surgery
Flap	10	11
Free		
Anterolateral thigh	2	2
Fillet	1	0
Medial sural	0	2
Lateral arm	0	1
Pedicled		
Groin	2	5
Fillet	3	0
Cross-finger	0	1
Local	2	0
Tendon transfer	12	8
Toe to hand transfer	0	7

Discussion

In reconstruction of the mutilated hand, the priorities are to obtain a functional thumb and restore at least two functional fingers in order to achieve the major goal of prehensile function.[11] An additional consideration that must not be overlooked is the appropriate management of associated hand injuries. Ideally, this results in tripod grip. Among the

Table 4 List of immediate tendon transfer

Donor	Recipient	Number
FDP	FDP	1
FDP	FDL	1
FDP	PL	1
FDS	FDP	2
EPL	EDC	1
EPL	Lateral band	1
EIP	EPL	1
EDC	EDC	1
EDC	EDM	1
FPL	FDP	1
FPL	FDS	1

Abbreviations: EDC, extensor digitorum communis; EDM, extensor digiti minimi; EIP, extensor indicus proprius; EPL, extensor pollicus longus; FDL, flexor digitorum longus; FDP, flexor digitorum profundus; FDS, flexor digitorum superficialis; FPL, flexor pollicis longus; PL, palmaris longus.

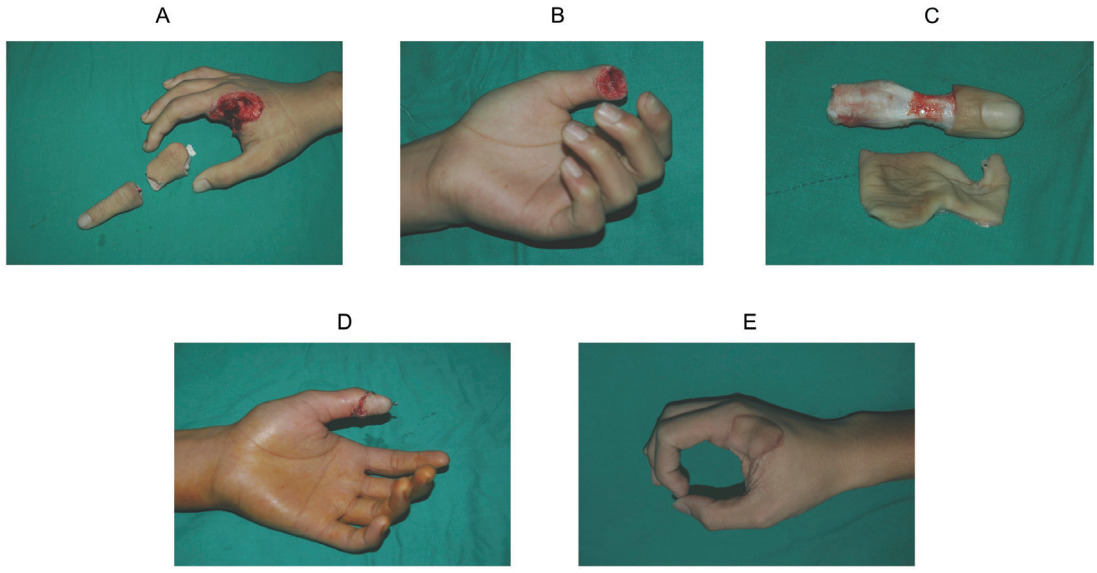

Fig. 1 A 16-year-old male sustained a sharp cutting injury to both hands by an industrial machine. (**A**) The right index finger was amputated at both proximal and distal to the metacarpophalangeal joint. (**B**) The left thumb was amputated at distal phalanx level. (**C** and **D**) The index finger was judged not to be suitable for replantation due to segmental injury. The distal part of the amputated index finger was therefore used for heterotopic digital replantation (HDR) to augment the stump of the left thumb, and (**E**) the proximal part of the amputated right index finger was used as a free fillet flap to cover exposed bone at the right index finger stump. The functional and cosmetic result for both hands was satisfactory at 36-month follow-up.

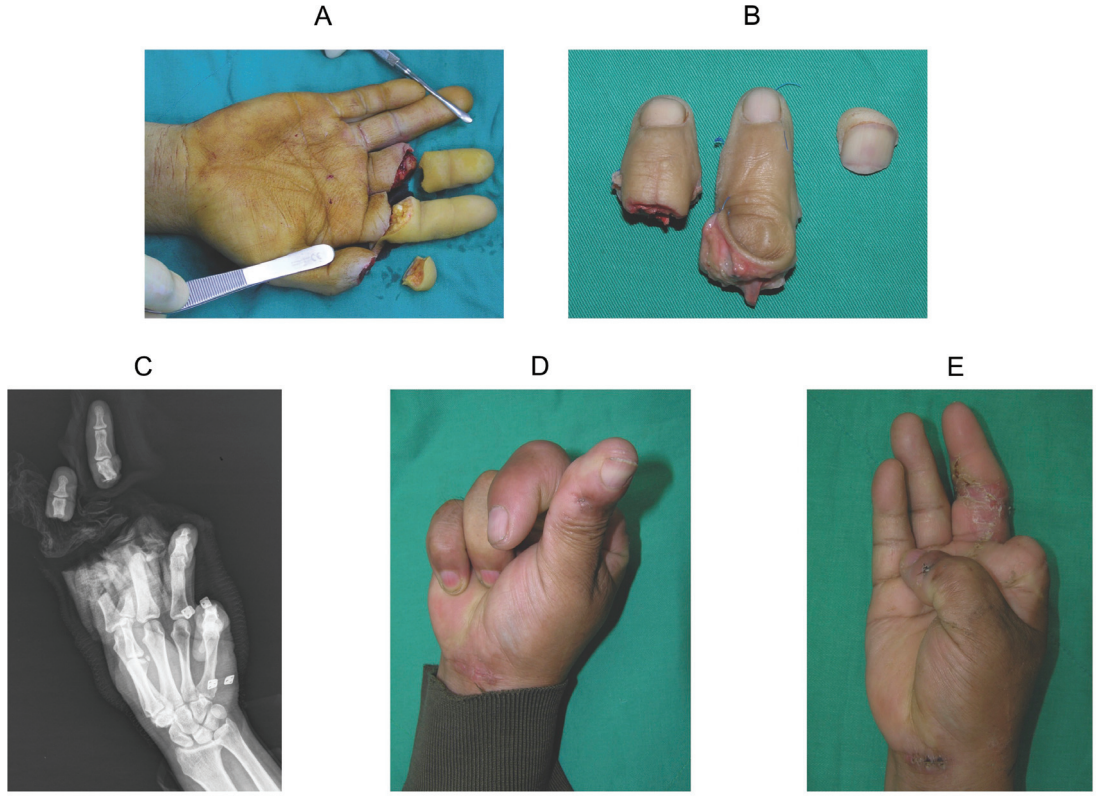

Fig. 2 A 54-year-old male sustained a knife injury to his right hand. (**A–C**) Amputation of right thumb, index, and middle fingers at the level of the nail root, proximal phalanx, and proximal interphalangeal joint, respectively. Orthotopic digital replantation (ODR) of the amputated thumb was not possible due to its inadequate length and insufficient bone stock. However, (**D**) heterotopic digital replantation (HDR) of the distal remnant of the middle finger was a perfect fit for the thumb defect. (**E**) To optimize global hand function, rather than performing ODR of the index finger, we chose to replace it heterotopically onto the middle finger stump. This provided both additional length and a mobile proximal interphalangeal joint (PIPJ) for the middle finger. A secondary flexor tenolysis for the middle finger was performed at 4 months. The functional result was satisfactory at 24-month follow-up.

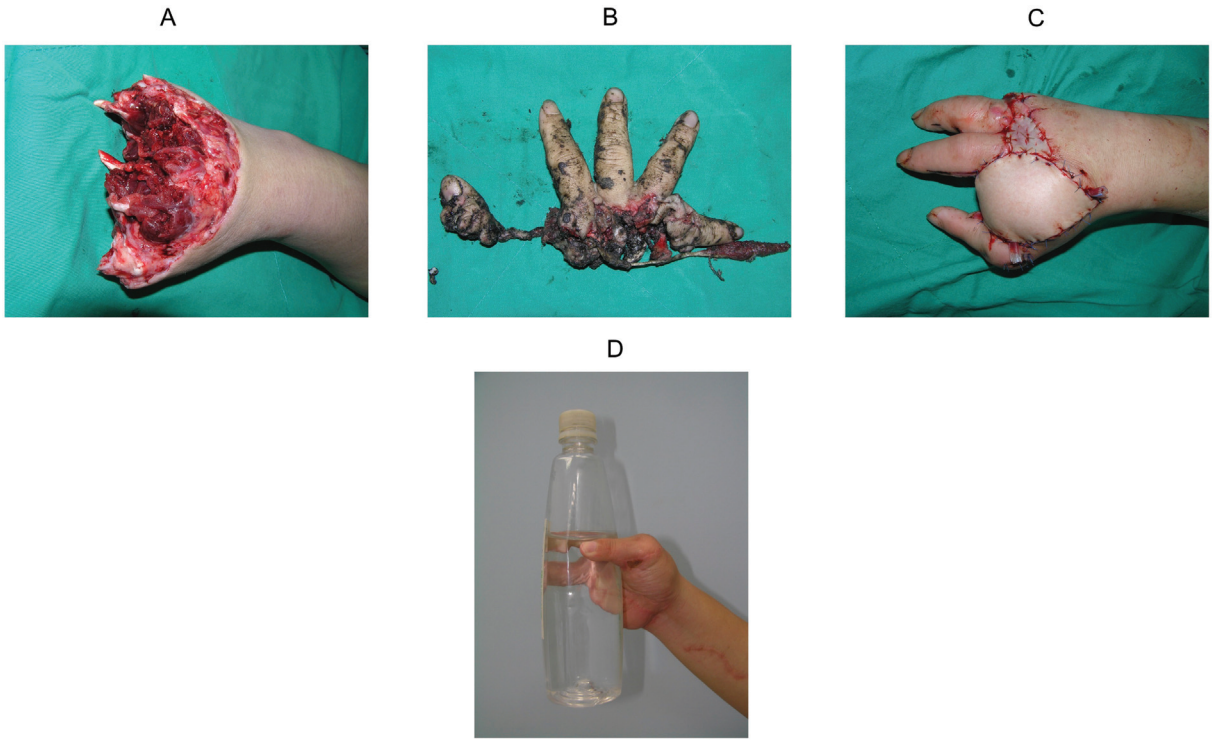

Fig. 3 A 22-year-old male industrial worker suffered (**A**) a transmetacarpal amputation resulting in metacarpal hand type 2A. (**B**) In examination of the injured part, the original thumb and small finger were deemed nonsalvageable. The thenar musculature was determined to be adequate. (**C**) Heterotopic digital replantation (HDR) of the amputated ring finger to the thumb stump and the amputated index and middle finger were heterotopically replanted to the third and fourth rays, respectively, and a medial sural artery perforator flap was used to cover the first web defect later. (**D**) The tripod grip was achieved, and the functional result was satisfactory at 11-month follow-up.

reconstructive options for traumatic amputations of multiple digits, ODR is the most straightforward option to restore function and appearance. However, the anatomic configuration of the surviving digits may not provide optimal hand function. In addition, injuries of the replanted digits in the form of skin, bone, joint, or tendon damage, may compromise the outcome. In such situations, HDR is an alternative which can provide a more functional and aesthetic result without inflicting additional donor site morbidity.[21] However, there are some unanswered questions regarding this technique, particularly related to HDR survival rates, functional outcomes, and the development of an inclusive strategy to prioritize when undertaking an HDR reconstructive approach. The associated English articles are summarized in ►**Table 5**.

In our study, the survival rate of HDR was 83.8% (57/68 digits), which is comparable to other HDR series.[6,10,14,15,22] Analysis of our failures revealed the success rate of heterotopically replanted thumbs (13/19, 68.4%) was significantly worse than heterotopically replanted fingers (44/49, 89.8%) ($p = 0.032$). We attribute this difference to the fact that we were more aggressive to restore a shortened thumb and may have compromised on the quality of spare parts in order to achieve replantation for thumb restoration. Although the overall survival rates of ODR and HDR are not significantly different, replantation of the thumb warrants particular care and attention.

As a result of the presented case experiences, we have summarized our clinical decision-making process for these complicated cases in ►**Fig. 4**. This figure highlights several key principles that must be considered while performing these reconstructions.

The first priority in multiple digital amputations is thumb restoration because it contributes 40 to 50% of hand function.[22] Reconstruction should aim to restore length, mobility, and sensation. Based on these factors, we classify amputated thumbs into three types. Type 1 is an amputation distal to the interphalangeal joint (IPJ). When HDR is considered for type 1 amputations, the aim is to choose similar size match for the amputated thumb as possible for better length (►**Fig. 4-1A**; ►**Figs. 1** and **2**). Type 2 is an amputation proximal to the IPJ. The aim of HDR for type 2 amputations is similar to type 1 amputations. However, pollicization and toe-to-thumb transfer should also be considered in this circumstance if HDR is not indicated (►**Fig. 4-1B**; ►**Fig. 3**). Type 3 is an amputation where there is associated injury to thenar muscles, bone, joint, or tendon, which may compromise the function of the thumb. We advocate that these other injuries be addressed at the same time as HDR. For example, a thumb amputation where the carpometacarpal joint is preserved but thenar muscles are largely destroyed can be treated with HDR. An immediate opponensplasty, using the redundant flexor digitorum superficialis of the amputated finger that was replanted onto the thumb, greatly improves thumb function with no additional donor site morbidity (►**Fig. 4-1C**).

The next priority in multiple digital amputations is to provide at least two opposable fingers. Amputation of the

Table 5 Major HDR series in English literature review

Reference	HDR case number	HDR recipient digit					Result
		Thumb	Index	Middle	Ring	Little	
Chiu et al, 1985[8]	2	1 (50%)	1 (50%)				100% survived
Soucacos et al, 1994[10]	34	6 (17.6%)	28 ulnar/index fingers (82.4%)				82.3% survived, proof of principle
Schwabegger et al, 1999[15]	11	4 (36.4%)	3 (27.3%)	3 (27.3%)		1 (9%)	100% survived, proof of principle
An et al, 2003[11]	5	2 (25%)	3 (37.5%)	1 (12.5%)	2 (25%)		100% tripod pinch, proof of principle
Engin and Aksakal, 2015[16]	1				1 (100%)		Satisfactory result, proof of principle
Kokkoli et al, 2015[12]	7	4 (36.4%)	3 (27.3%)	1 (9%)	3 (27.3%)		100% survived, proof of principle
Current study	53	19 (27.9%)	8 (11.8%)	21 (30.9%)	17 (25%)	3 (4.4%)	83.8% survived, provide algorithm

Abbreviation: HDR, heterotopic digital replantation.

fingers can be classified as a metacarpal hand (loss of all digits) (►**Fig. 4-2A**; ►**Fig. 3**), loss of radial (index ± middle ± ring) or ulnar (little ± ring ± middle) digits (►**Fig. 4-2B**; ►**Fig. 2**), loss of alternate fingers (index and ring; middle and little) (►**Fig. 4-2C**), or other combinations, such as loss of central (middle and/or ring) digits or loss of both radial and ulnar digits (►**Fig. 4-2D**). A metacarpal hand requires restoration of at least two functional digits. Wei et al found grip strength to be greater when replanting digits to the ulnar stumps of the hand.[6] In contrast, if the patient requires better

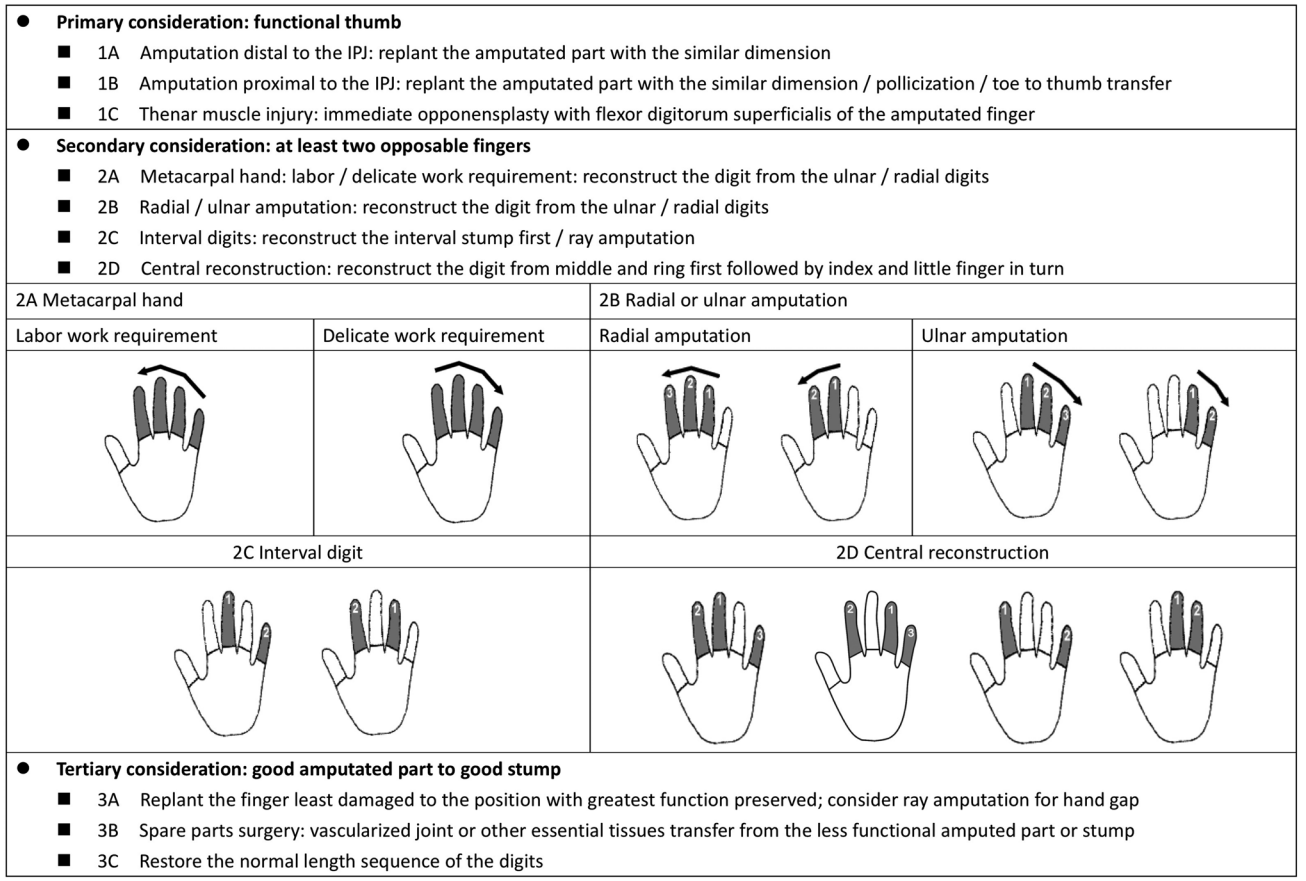

Fig. 4. Guidelines for hand reconstruction with heterotopic digital replantation (HDR).

dexterity for more delicate work, digits are best reconstructed on the radial side of the hand. A compromise between these differing positioning strategies is to reconstruct middle and ring fingers. This provides some degree of power grip, an adequate first web space, as well as precision grip.[2,6,17]

Replantation of multiple radial or ulnar digit amputations should start from adjacent to an uninjured finger to avoid a mid-hand gap (►**Fig. 4-2B**).[2] This principle also governs reconstruction of amputations of alternate digits (►**Fig. 4-2C**), where reestablishing three contiguous fingers is the priority. If this is not possible, ray amputation should be considered.[22] Management of other rare amputation combinations (►**Fig. 4-2D**) should prioritize reconstruction of the central rays (middle and ring fingers) to prevent gapping. This consideration is reflected in the higher percentage of middle (73.8%) and ring finger (73%) reconstructions undertaken than for index (28.9%) and little finger (25.9%) in our series (►**Table 2**). In summary, the vast majority of multiple amputations can be managed by reconstructing digits in the following order: middle, ring or index, index or ring, followed by the little finger.

The third consideration is the management of any associated hand injury. This is relevant to the first and second considerations, because amputated parts should not be replanted onto a poor-quality stump. A low-quality finger stump may be best treated with completion ray amputation to close the mid-hand gap (►**Fig. 4-3A**; ►**Fig. 2**). When the amputated digit is judged unsuitable for replantation, it should be borne in mind that the remnant can be used for "spare parts" to reconstruct other injuries within the hand. Useful components may include skin, soft tissue, nail bed, nerve, vessel, bone, joint, and tendon (►**Fig. 4-3B**; ►**Fig. 1**).[22] It may even be possible to design a small free flap or vascularized joint transfer to improve function.[23] More extensive injuries, such as skin and soft tissue defects, tendon loss, and proximal neurovascular injuries may require reconstruction and immediate soft tissue cover. Flaps, either distant or free, have advantages and disadvantages. Our preference is the free cutaneous flap due to its flexibility with insetting, ease of reelevation should secondary reconstruction be required, and the fact that rehabilitation is not delayed by having a limb tethered to a distant pedicled flap. However, some patients present with an extensive zone of trauma that limits the availability of recipient vessels and predisposes to vasospasm. One should also be mindful of preserving potential recipient vessels for secondary toe transfer. In our series, 10 cases required immediate flap reconstruction, including three free flaps, five pedicled flaps, and two local flaps. When all possible functional requirements are met, an attempt should be made to restore the normal length sequence of the digits (►**Fig. 4-3C**). This can improve the overall cosmetic appearance of the hand that many patients appreciate. Secondary surgery was occasionally required: 11 cases had late flap reconstruction, 8 required secondary tendon transfer, and 5 cases received seven secondary toe-to-hand transfers to achieve four tripod grip and one pulp pinch. ►**Fig. 4** shows the management algorithm that summarizes our approach to the mutilated hand with multiple amputated digits. We believe this is a useful guide for management in the acute setting, when clinical decisions are inevitably made under a degree of time pressure.

When reviewing the previous larger series of HDR, some major contributions can be appreciated. Soucacos et al in a series of 34 patients provided a concise and useful classification to describe the indication for HDR.[10] They outline the five major indications as: multiple digital amputations including the thumb, bilateral thumb amputations, bilateral symmetrical digital amputations, multiple digital amputations with the thumb intact, and amputation of all five digits. Their classification scheme is useful in providing a treatment strategy for a given mutilating hand scenario with their treatment preferences encouraging ulnar-sided replantation. Kokkoli et al[12] recently provided a useful synopsis of reconstructive tools describing the heterotopic tools available to the hand surgeon. Although we agree with their sentiment that these injuries are extremely complex, we attempted to provide a more concrete algorithm for surgeons who would encounter this problem frequently. Instead of providing an overall heuristic, we take patient and injury-specific factors into account to determine the optimal intraoperative strategy for heterotopic replantation. More specifically, we usually opt for replantation toward obtaining functional central unit of the hand, achieving compromise between the precision grip of radial-sided digits with that of the power grip of ulnar side of the hand.

In an era of rising health care costs and increased patient expectation, hand surgeons as a group are obliged to provide more comprehensive outcomes as emphasized by Sebastin and Chung.[21] With this information, we can provide better counseling to our patients and provide realistic outcome data to third-party payers. With HDR, the previous outcomes reports have ranged from "satisfactory functional result and cosmetic appearance"[10] to tripod grip[11] to more comprehensive reports of sensory function with range of motion data.[15] In the present study, we have chosen to report the acquisition of tripod and pulp pinch as our major outcome measure since this is the primary goal in the setting of mutilating hand injury.

Conclusion

Following mutilated hand injuries with multiple finger amputations, HDR has many advantages over ODR when trying to optimize functional outcomes. The best amputated parts are reserved for thumb reconstruction and two opposable, adjacent fingers in order to achieve tripod grip. Other injuries that would compromise overall hand function should be corrected simultaneously. As with all ventures in reconstruction of the mutilated hand, the operative plan must take into account the patient's age, occupation, mechanism of injury, functional demands, expectations, motivation, comorbidities, associated injuries, and psychological status. Ultimate functional outcomes are influenced by the

success of patient education, rehabilitation, and any secondary reconstructive surgery performed.[9]

Authors' Contributions

Experimental design was done by N.J.C. and C.H.L. Data gathering was performed by N.J.C., N.S.S., W.Y.C., Y.C.C., Y. T.L., C.H.L., and C.H.L. Data interpretation and analysis were done by C.C.H. and H.D. The primary draft of the manuscript was written by N.J.C. and C.C.H. H.D. advised in initial draft of manuscript. Review of the final manuscript was performed by C.H.L. All authors read and approved the final manuscript.

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Conflict of Interest

None declared.

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