Reconstruction techniques for upper extremity crush injuries with massive tissue loss and open fractures: a prospective study

B. KUŞCU[1], K. GURBUZ[2], F. DOGAR[3]

[1]Bandırma Special Royal Hospital, Orthopedics and Traumatology, Balıkesir, Turkey
[2]Clinics of Orthopedics and Traumatology, Education and Research Hospital, Kayseri, Turkey
[3]Department of Orthopedics and Traumatology, Sutcu Imam University Hospital, Kahramanmaraş, Turkey

Abstract. – OBJECTIVE: Crush injuries and open fractures are often accompanied by extensive tissue loss, rendering clinical and surgical management quite challenging, particularly in the upper extremities. The primary goal in these cases is to obtain a functional and cosmetically acceptable limb. However, the management of complex crush injuries (involving extensive tissue loss and open fractures) is associated with a variety of complications, ranging from infection to amputation. In this study, we aimed to analyze the clinical outcomes of reconstruction for managing complex upper extremity crush injuries.

PATIENTS AND METHODS: We reviewed the clinical and surgical data of patients with complex upper extremity crush injuries who were treated at five Level III trauma centers between July 2012 and December 2022. Patients with an injury that could not be replanted at the time of trauma, those who succumbed to the injuries before reconstruction, and patients with a postoperative follow-up time of < 1-year, missing data, or lost to follow-up were excluded. Data regarding demographic characteristics, clinical examination, radiological images, mechanism of injury, orthopedic or non-orthopedic injuries, comorbidities, tissue loss size, surgical procedures, number of debridement and first debridement time, complications, number of days of hospitalization and, if any, intensive care unit stay, were recorded.

RESULTS: Twenty-one patients were included in the study (mean age = 37.4 ± 7.25; range = 16-62 years; 17 males, 4 females). Road traffic accidents were the most frequently documented cause of injury. The mean time to the first reconstruction was 4.2 ± 1.2 days. Tissue defect sizes ranged from 6 × 4 cm to 18 × 12 cm. Anterolateral thigh flaps, latissimus dorsi flaps, radial forearm, and lateral arm flaps, with sizes ranging from 3 × 6 cm to 18 × 26 cm, were used in the patients.

CONCLUSIONS: Simple reconstruction techniques, such as skin grafts or island flaps, can provide satisfactory results in terms of both appearance and function in upper extremity crush injuries with significant bone exposure and large soft tissue defects.

Key Words:
Upper extremity, Crush injury, Reconstruction, Flap.

Introduction

Upper extremity crush injuries present a formidable challenge for surgeons due to the complex nature of extensive tissue defects and multiple open fractures[1]. Unlike lower limb injuries, managing tissue defects in the upper extremity requires a multifaceted approach beyond mere wound coverage post-fracture fixation. The primary objective in treating upper extremity crush injuries is to achieve optimal functional recovery and aesthetic outcomes while minimizing donor site morbidity, averting life-threatening infections, and ensuring adequate soft tissue protection for critical structures like nerves and vessels. This intricate task necessitates the consideration of various surgical techniques and their combinations to address the complexity of these injuries[2,3]. Recent literature emphasizes the importance of understanding indications for upper extremity replantation and the management of complex upper limb trauma to enhance treatment strategies and outcomes[4,5]. These articles shed light on the nuanced decision-making processes involved in determining the appropriateness of replantation procedures and the comprehensive management of intricate upper limb traumas. By incorporating insights from these recent studies, we aim to enrich the discussion on the indications

Corresponding Author: Burak Kuşcu, MD; e-mail: dr.burakkuscu@hotmail.com

and management strategies for upper extremity crush injuries in our study. In this research, we present detailed surgical interventions and postoperative outcomes for 21 patients with complex upper extremity crush injuries characterized by significant tissue loss and multiple open fractures. Through our study, we seek to contribute valuable clinical evidence regarding the efficacy of different reconstruction techniques in optimizing outcomes for patients with such challenging injuries.

Patients and Methods

We analyzed all patients with upper extremity crush injuries treated by the authors between July 2012 and December 2022 at five Level III trauma centers. Of these, patients undergoing reconstruction with massive tissue loss and open multiple fractures of the upper extremities were included in the study. Patients with an injury that could not be replanted at the time of trauma (Figure 1) or those who succumbed to the injuries before reconstruction (Figure 2) were excluded. In addition, five patients who did not agree to participate in the study, with missing data, were lost to follow-up or had a postoperative follow-up time of less than 1 year, were excluded from the study. Accordingly, 21 patients were included in the final analysis.

Informed consent was obtained from all participants for the capture and publication of their clinical photographs. The study protocol was approved by the Ethics Committee of Necmettin Erbakan University (approval number: 2023/4296). The principles outlined in the Declaration of Helsinki were followed throughout the study.

We reviewed the patients' demographic and clinical data, including details from clinical examinations and radiographs, to ascertain the following information: age, sex, cause of trauma, co-morbidities, time to first debridement, number of washouts and debridement, tissue defect size and localization, type of reconstructive solution used, incidence of clinical infection, coexisting orthopedic and non-orthopedic injuries, and the total length of hospital stay (including the intensive care unit stay).

Statistical Analysis

The statistics were analyzed using the SPSS version 17.0 software (SPSS Inc., Chicago, IL, USA). The characteristics of the subjects were summed up and presented using descriptive statistics, mean and standard deviation for continu-

Figure 1. Image showing of a traffic accident in which a truck hit a motorcyclist from the rear. The patient's left hand was amputated between the front wheel of the motorcycle and the crushed truck.

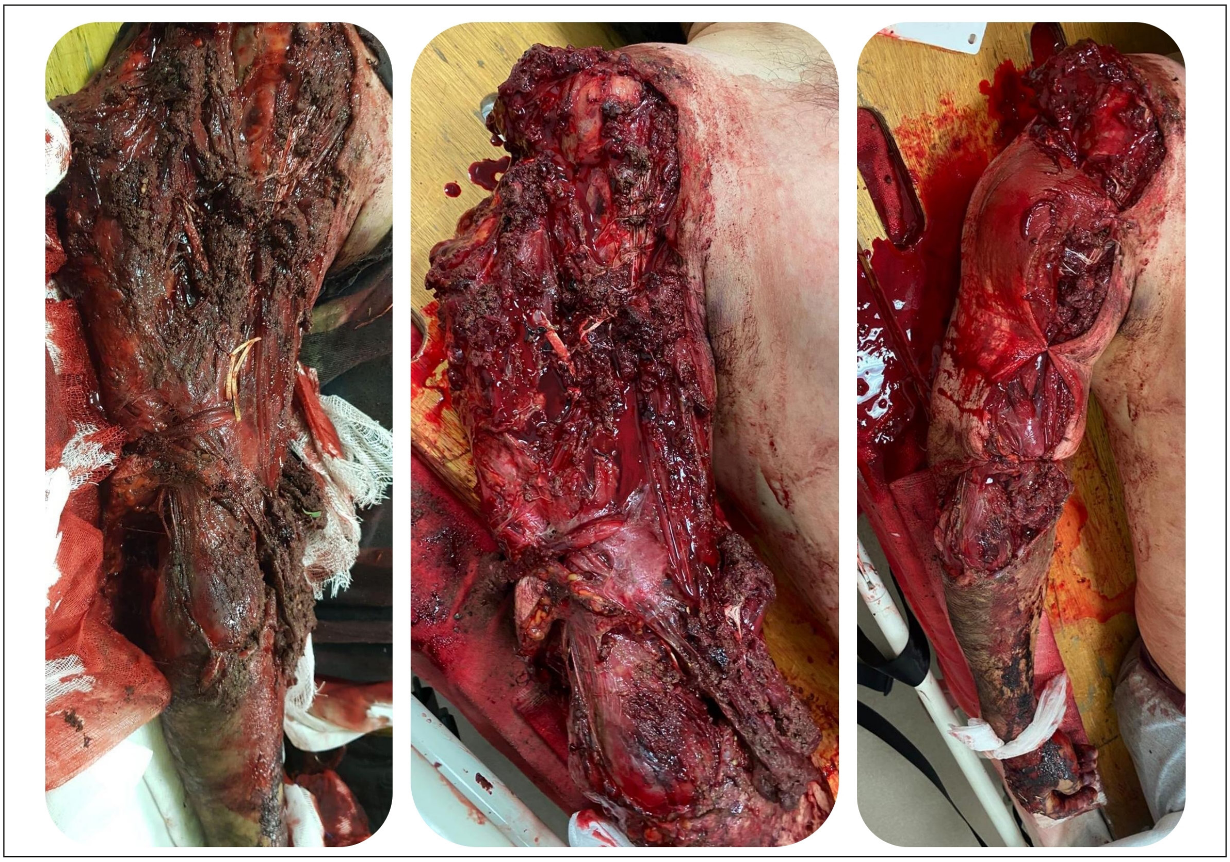

Figure 2. Image showing a traffic accident involving a drunk car driver who was not wearing a seat belt. The driver was thrown out of the windshield and dragged over his right upper extremity. The patient sustained life-threatening traumatic cranial and thoracic injuries and failed to survive.

ous variables and frequency and percentage for categorical variables. Kolmogorov-Smirnov tests were used to check the continuous variables for Gaussian distribution. *t*-tests were used for all the continuous variables with a Gaussian distribution.

Results

Among the 21 patients, there were 17 males and four females, with an average age of 37.04 ± 7.25 years (range = 16-62 years). All patients had sustained complex crush upper-extremity injuries, of which the most common cause of death was due to automobile collisions.

The average time required for reconstruction was 4.2 ± 1.2 days (range = 0-8 days). For all patients, initial debridement using a loupe and a tourniquet to remove the infected and contaminated tissues was followed by wound irrigation with at least 6 L of saline solution. After the wounds had been completely debrided, the fractures were fixed in one stage, either internally or externally, and vacuum-assisted closure (VAC) was used to cover the remaining wounds. During the subacute phase, reconstruction was performed using a skin flap or a skin graft. During the study period, a total of 15 flaps were used to reconstruct 15 different upper extremities. Flap selection was based on the size of the wound and the underlying muscle and soft tissue deficiency. The following reconstruction techniques were used in the study patients: anterolateral thigh (ALT) flap, latissimus dorsi flap, radial forearm flap, and lateral arm flap. The size of tissue defects in the study patients ranged from as small as 6 × 4 cm to as large as 18 × 12 cm. The ALT flaps varied from 8 to 22 cm in length and 6-16 cm in width. The latissimus dorsi flaps were 18-26 cm in length and 7-9 cm in width. The lateral arm flaps were 4-10 cm long and 3-6 cm wide. Table I summarizes the details of the different reconstruction solutions, postoperative flap complications, infection statistics, and flap outcomes for the 21 patients.

Table I. Summary of the study patients and the reconstruction techniques used.

#	Age and sex	Cause of trauma	Co-morbidity	Radiological diagnosis of traumatic upper extremity	Fracture fixation	Time to first debridement (hours)/Number of washouts, and debridement	Soft tissue defect size (cmxcm) and location	Reconstructive solution	Flap failure and comments	Clinical infection at reconstruction donor and/or recipient sites	Associated orthopedic co-exist trauma	Associated non-orthopedic co-exist trauma	ICU Stay (days)	Total hospital stay (days)
1	34 M	Traffic accident	-	Radius and ulna segmental shaft fractures, radial distal end, ulna styloid fractures	In	14/6, 6	15x10, dorsum of the wrist	Radial flow-through free musculofasiocuta-neous ALT flap	Partial flap loss, overcome by debridement and splint-thickness skin grafting	-	Ipsilateral femur shaft fracture, contralateral bimalleolar ankle fracture	Pneumothorax overcome by thoracal tube	5	29
2	57 M	Traffic accident	HT	Ulna proximal fracture with bone defect	In	35/1, 11	8x6, posterior site of the elbow	Avascular fibula grafting + lateral arm fasiocutaneous island flap	-	-	Contralateral tibia segmental fracture, 3rd-4th metatarsal fracture	Liver laceration (operated)	11	44
3	16 M	Traffic accident	Type 1 DM	Radius and ulna shaft fractures	In	8/2, 1	6x4, dorsum of the mid-forearm	VAC + splint thickness skin grafting	-	-	Ipsilateral shoulder dislocation	-	-	5
4*	62 M	Traffic accident	Bipolar disorder, HT	Radial segmental, ulna 1/3 distal shaft, radial styloid, 2nd and 5th metacarpal shaft, and proximal phalanx of thump shaft fractures	In and Ex	23/6, 5	19x10, dorsum of the forearm	VAC + full thickness skin grafting	-	-	Ipsilateral tibia shaft and clavicula fracture	Splenic laceration (no need to operate)	12	34
5	44 M	Machine strangulated	-	Radius and ulna shaft, radial styloid and olecranon fractures	In	7/3, 3	7x11, medial 1/3 proximal site of the forearm	Radial flow-through free musculofasiocutaneous ALT flap	-	Superficial at donor site	Ipsilateral elbow dislocation	Contusio cerebri	5	27
6	45 F	Traffic accident	Hypo-T	Humerus shaft fracture	In	8/4, 3	8x14, postero- superior site of elbow	Latissimus Dorsi musculofasiocuta- neous island flap	-	Superficial at recipient site	Ipsilateral shoulder dislocation	-	-	12
7	38 M	Traffic accident	-	Radial segmental, ulna 1/3 distal shaft fractures	Ex	11/2, 1	9x11, postero-lateral site of the shoulder	Latissimus dorsi fasiocutaneous free flap	Microvascular re-anastomosis	-	Ipsilateral scapula, and lumbar L3-4-5 fractures	Contusio cerebri	9	32
8¥	34 M	Hot machine crushed	-	2nd and 3rd metacarpal shaft fractures	In	4/1, 1	7x8, dorsum of the hand	Reverse flow radial forearm fasiocutaneous island flap	-	-	-	-	-	5
9	39 M	Chainsaw	-	Ulna 1/3 proximal shaft and elbow dislocation	In	4/1, 1	18x12, posterior of the elbow	Latissimus dorsi musculofasiocuta- neous island flap	-	-	-	-	-	11
10	30 M	Traffic accident	-	Radius and ulna segmental fracture	Ex	8/5, 3	5x8, medial site of the forearm	VAC + splint thickness skin grafting	-	Superficial at donor site	Ipsilateral acetabulum and femur shaft fractures	Pneumothorax overcome by thoracal tube	4	38

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Table I ***(Continued).*** Summary of the study patients and the reconstruction techniques used.

#	Age and sex	Cause of trauma	Co-morbidity	Radiological diagnosis of traumatic upper extremity	Fracture fixation	Time to first debridement (hours)/Number of washouts, and debridement	Soft tissue defect size (cmxcm) and location	Reconstructive solution	Flap failure and comments	Clinical Infection at reconstruction donor and/or recipient sites	Associated orthopedic co-exist trauma	Associated non-orthopedic co-exist trauma	ICU stay (days)	Total hospital stay (days)
11	32 M	Traffic accident	-	Radius proximal shaft fracture	In	7/3, 2	9x6, medial side of the elbow	Lateral arm fasiocutaneous island flap	Partial flap loss, overcome by debridement and splint-thickness skin grafting	-	Bilateral acetabular fracture, ipsilateral hip dislocation	Subarachnoid hemorrhage	9	39
12	33 M	Traffic accident	-	Radial caput fracture and elbow dislocation	In	6/3, 2	8x9, anterior site of the mid-forearm	VAC + splint thickness skin grafting	-	-	-	-	-	6
13	27 M	Traffic accident	-	Olecranon fracture	In	6/1, 1	5x9, postero-superior site of elbow	Lateral arm fasiocutaneous island flap	-	-	Ipsilateral tibia and femur supracondylar fractures	Pneumothorax overcome by thoracal tube	3	17
14	36 F	Hot machine crushed	-	Humerus shaft fracture	In	6/5, 4	9x8, postero-medial site of the shoulder	Lateral arm fasiocutaneous island flap	-	Superficial at donor site	Ipsilateral shoulder dislocation	Contusio cerebri	2	14
15	44 F	Machine strangulated	-	Radius and ulna shaft, radial styloid fractures	In	8/2, 1	5x4, lateral site of the mid-forearm	VAC + full thickness skin grafting	-	-	Ipsilateral humerus fracture	-	-	7

Continued

Table I *(Continued)*. Summary of the study patients and the reconstruction techniques used.

#	Age and sex	Cause of trauma	Co-morbidityy	Radiological diagnosis of traumatic upper extremity	Fracture fixation	Time to first debridement (hours)/number of washouts, and debridement	Soft tissue defect size (cmxcm) and location	Reconstructive solution	Flap failure and comments	Clinical Infection at reconstruction donor and/or recipient sites	Associated orthopedic co-exist trauma	Associated non-orthopedic co-exist trauma	ICU stay (days)	Total hospital stay (days)
16	29 M	Traffic accident	-	2nd, 3rd and 4th metacarpal fractures	In	4/1, 1	5x4, dorsum of the wrist	Reverse flow radial forearm fasiocutaneous island flap	-	-	Radius distal end fracture	Rip fractures	-	5
17[ɣ]	47 M	Traffic accident	-	Humerus shaft fracture	Ex	17/2, 1	11x9, media site of upper arm	Latissimus dorsi musculofasiocutaneous island flap	-	-	Ipsilateral femur distal, tibia shaft fractures	Pneumothorax overcome by thoracal tube	13	37
18	53 M	Machine strangulated	HT	Ulna fracture	In	6/1, 1	7x4, posterior 1/3 proximal of the forearm	Lateral arm fasiocutaneous island flap	-	Superficial at recipient site	-	-	-	19
19	31 M	Machine strangulated	-	Radius and ulna shaft fractures	In	4/1, 1	6x8, lateral site of the 1/3 proximal forearm	Lateral arm fasiocutaneous island flap	Partial flap loss, overcome by debridement and seconder wound healing	-	Ipsilateral shoulder dislocation, lumbar L5-S1 and ipsilateral calcaneus fractures	-	1	11
20	23 F	Traffic accident	PCOS	3rd, 4th and 5th metacarpal fractures	In	7/1, 1	4x6, dorsum of the hand	Reverse flow radial forearm fasiocutaneous island flap	-	-	-	-	-	5
21	39 M	Traffic accident	-	Radius and ulna segmental fractures	In	6/2, 1	8x6, postero- lateral mid-forearm	VAC + splint thickness skin grafting	-	-	Ipsilateral iliac crest fracture	-	-	7

[*]Representative case 1
[¥]Representative case 2
[ɣ]Representative case 3

ICU: intensive care unit
M: male
F: female

DM: diabetes mellitus
HT: hypertension
Hypo-T: hypothyroidism
PCOS: polycystic ovary sendrome

In: internal
Ex: external
VAC: vacuum assisted closure

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Representative Cases

Case 1

A 62-year-old man involved in a traffic accident was thrown from his vehicle and dragged over his right upper extremity. He sustained complex injuries on the extensor side of the forearm with skin avulsion from the right hand, along with fractures of the radius (segmental), ulnar shaft (distal third), radial styloid process, shafts of the second and fifth metacarpals, and thumb (shaft of the proximal phalanx). The segmental ulnar artery defects observed were reconstructed; fortunately, the ulnar nerve was spared. Plates were used for bone reduction and internal fixation. Then, thorough and extensive debridement was performed, followed by VAC sessions; eventually, full-thickness skin transplantation was carried out. At nine months postoperatively, the patient had a flexion range of 50° and an extension range of approximately 60° in his right wrist joint (Case #4, Figure 3 and Table I).

Case 2

The left hand of a 34-year-old man was crushed by a heated press machine, causing skin avulsion over the extensor side of the hand, severe extensor tendon and muscle injuries, and shaft fractures of the second and third metacarpals. Exploration and emergency debridement were arranged. All de-vascularized tissues were debrided as thoroughly as possible. Fractures were repaired using dynamic compression plates. The defect was repaired using a radial forearm fasciocutaneous island flap with reverse flow. The donor site was covered with the epidermis of the split-thickness graft. At nine months postoperatively, the patient had about 70° of flexion and 60° of extension range of motion in the left wrist. In addition, the texture and appearance of the flap were satisfactory at the 11-month follow-up (Case #8, Figure 4).

Case 3

A 47-year-old man was involved in a traffic accident in which he was jammed between two vehicles. The accident resulted in compartment syndrome of the right upper extremity and a humeral shaft fracture. Emergency exploration revealed defects in the brachial artery, which were successfully reconstructed; fortunately, the nerves were spared. The compartment pressure was surgically relieved by performing fasciotomies in both the arm and forearm. The forearm fasciotomy was closed with regular sutures, but the medial aspect of the arm required reconstruction with a latissimus dorsi musculofasciocutaneous island flap. The donor site was sutured to close. The humeral shaft fracture was reduced and fixed using a plate. At nine months postoperatively, we achieved approximately 80° of flexion and 60° of extension range of motion at the right elbow. Eight months after the procedure, the flap had a velvety texture with satisfactory cosmesis (Case #17, Figure 5, Table I).

Discussion

This study demonstrates the successful management of complex upper extremity injuries through reconstruction using different flaps, including ALT, latissimus dorsi, radial forearm, and lateral arm flaps. Previous studies have reported a higher incidence of upper extremity injuries in males than in females[6,7], which was also observed in our study sample (male:female = 4.25:1). Furthermore, traffic accident-related injuries were the major etiology in this study, which concurs with the existing literature that reports motor vehicle accidents as one of the leading causes of upper extremity injuries[7,8].

The average time to reconstruction in our patients was 4.2 ± 1.2 days (range = 0-8 days). Early reconstruction of upper extremity injuries is crucial for optimizing functional outcomes and reducing complications[9,10], as demonstrated in our patients. Additionally, the use of VAC for wound coverage after debridement and fracture fixation is a common approach used in the management of complex upper extremity injuries[11,12], which helps promote wound healing, reduce infection rates, and prepare the wound for subsequent flap or skin graft reconstruction.

The present study illustrates that various reconstruction techniques, ranging from basic to intricate, encompassing skin grafts and free flaps, can yield satisfactory outcomes in terms of both visual appeal and functional outcomes in cases of crush injuries affecting the upper extremities, characterized by substantial bone exposure and extensive soft tissue damages. It is important to note that, like any surgical procedure, the use of skin grafts or island flaps carries certain risks. These risks include infection, tissue necrosis, loss of limb function, scarring, bleeding, and potential reparative delay. These risks are primarily influenced by factors, such as the patient's age, gener-

Figure 3. Clinical pre-, peri-, and postoperative views of Case #4. The patient was a driver-seat-side passenger involved in a traffic accident who was not wearing a seat belt. He was thrown out of the car from the front windshield to the road and dragged over the right upper extremity. The tissue defect was reconstructed with full-thickness skin grafting after treatment using vacuum-assisted closure.

Figure 4. Clinical intra- and postoperative views of Case #8. The patient got his left hand crushed in a hot press machine. Reconstruction was performed using a reverse-flow radial forearm fasciocutaneous island flap.

al condition, and the presence of co-morbidities. Hence, the selection of the flap type and the surgical planning must be meticulously and individualized for each patient, taking into account their specific requirements and health circumstances[13].

The selection of the appropriate flap for reconstructive surgery is a critical decision that impacts the outcome of the procedure. We often consider various factors when choosing a flap, such as the size and location of the defect, patient-specific characteristics, and the desired aesthetic outcome. Recent studies have shed light on the importance of these considerations in flap selection[14-16]. One recent study by Mett et al[14]

Figure 5. Clinical intra- and postoperative views of Case #17. The patient involved in a road traffic accident developed compartment syndrome in the arm and forearm along with a humeral shaft fracture. Reconstruction was performed with a latissimus dorsi musculofasciocutaneous island flap after vacuum-assisted closure of the wound.

highlights the significance of body mass index (BMI) in predicting the thickness of free flaps, which can influence a surgeon's choice based on the defect location. The choice of flap type in our study was primarily determined by the size and location of the defect. Similarly, the study by Ikeguchi et al[15] focuses on using the anterolateral thigh (ALT) flap for upper extremity reconstruction, offering valuable insights into how defect localization influences flap selection. Based on their findings, the ALT flap is recommended as the first choice for upper extremity reconstruction. Additionally, Kang et al[16] discuss 35 patients ranging in age from 23 to 69 years with complicated upper extremity traumatic injuries who were treated using flap reconstruction in the subacute period. Their study mostly included cases of upper extremity traumatic defect reconstructions and reported two instances of wound healing complications (separation and epidermolysis) but noted an absence of surgical site infections, which were not encountered in our patients. The ALT, latissimus dorsi, radial forearm, and lateral arm flaps used for tissue transfer in our study are well-recognized for their versatility and reliability in reconstructing complex upper extremity injuries[17-19]. The dimensions of the flaps used in this study were within the reported ranges for each flap, which further supports their feasibility in upper extremity reconstruction[20,21].

Soft tissue repair procedures should indeed be simple, versatile, and safe to ensure optimal outcomes for patients. The choice of a highly qualified surgeon is paramount in minimizing risks and achieving the best possible results. Research by Kornman et al[22] highlights the importance of surgeon expertise in microsurgical reconstruction, emphasizing the correlation between surgical skill and patient outcomes. Also, postoperative rehabilitation plays a crucial role in the success of soft tissue reconstruction. Patients should be educated and encouraged to follow an appropriate and individualized rehabilitation program to maximize flap function. A previous study by Ooi et al[23] emphasizes the significance of postoperative rehabilitation in improving functional outcomes and patient satisfaction following soft tissue reconstruction procedures. Furthermore, patients' ability to adapt to the new situation and learn how to use the reconstructed flap is essential for achieving acceptable neuro-sensory perception and proprioceptive function. Proper rehabilitation can aid in enhancing proprioceptive feedback and functional outcomes postoperatively. Research by Georgescu et al[24] underscores the importance of patient education and training in optimizing sensory perception and motor function following upper limb reconstruction.

Upper extremity defects present a challenging scenario in reconstructive surgery, often requiring intricate solutions for optimal functional and aesthetic outcomes. Various flap options have been explored to address these complex defects. For instance, the anterolateral thigh (ALT) flap has been utilized for upper extremity reconstruction in older patients, offering compatibility with the soft tissue of the upper limbs and the flexibility to adjust flap thickness to match the hands' requirements. Additionally, the free vascularized medial femoral condyle corticocancellous flap has shown promise in treating challenging upper extremity nonunions, providing a viable solution for specific cases. The use of free tissue transfer, such as the free fillet flap, has been crucial in reconstructing severe traumatic injuries necessitating amputation in the upper extremities. These advancements in flap techniques and procedures underscore the importance of tailored approaches to upper extremity defect reconstruction, considering factors like defect location, patient characteristics, and functional requirements to achieve optimal outcomes and patient satisfaction[25,26].

There were certain limitations to this study. The sample size was relatively small, and the surgeries were conducted by the same surgical team, which may limit the generalizability of our findings. In addition, we did not include long-term functional or patient-reported outcomes, which could have provided more comprehensive information on the success of the reconstruction procedures. Further studies with larger sample sizes, multi-center designs, and longer follow-up periods are warranted to validate the findings of this study.

Conclusions

This study highlights that meticulous management and timely surgical intervention allow successful reconstruction of devastating upper limb crush injuries, with low rates of flap failure, infection, and amputation. Furthermore, the treatment for open fractures of the upper extremity should focus on ways to achieve soft tissue coverage rather than solely the operative timing for early coverage. In cases of extensive soft tissue defects without obvious bone exposure, simple reconstruction techniques, such as skin grafting or island flap, can provide satisfactory results in terms of both cosmesis and function, with minimal complications. Additionally, for restoration of elbow function, the latissimus dorsi flap may be preferred because of its ability to provide good dynamic muscle tissue for both the flexor and extensor muscle groups, thus optimizing functional outcomes.

Conflict of Interest

The authors declare that they have no competing interests.

Authors' Contributions

BK: conception, design of the work, data acquisition, analysis, figures preparation, wrote the main manuscript, drafted the work. KG: conception, design of the work, data acquisition, analysis, prepared the figures, wrote the main manuscript, drafted the work. FD: conception, design of the work, figures preparation, wrote the main manuscript. All authors read and approved the final manuscript.

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Availability of Data and Materials

The datasets analyzed during the current study are available from the corresponding author upon reasonable request.

Ethics Approval

This study was approved by the Ethics Committee of Necmettin Erbakan University under the approval 2023/4296 and carried out in accordance with the ethical standards set out in the Helsinki Declaration.

Informed Consent

Each patient provided written informed consent for participation in the study and for their photos to be published.

ORCID ID

B. Kuşcu: 0000-0002-1082-2206
K. Gurbuz: 0000-0002-0144-5517
F. Dogar: 0000-0003-3848-1017

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