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Corresponding author:

Sang Hyun Lee

Department of Orthopaedic Surgery,
Medical Research Institute, Pusan
National University Hospital, 179
Gudeok-ro, Seo-gu, Busan 49241, Korea
Tel: +82-51-240-8718

Fax: +82-51-247-8395

E-mail: handsurgeon@pusan.ac.kr

ORCID:

<https://orcid.org/0000-0002-2084-9824>

Forearm replantation: pearls and pitfalls

Dong Hee Kim¹, Sang Ho Kwak², Sang Hyun Lee³

¹Department of Orthopedic Surgery, Samsung Changwon Hospital, Sungkyunkwan University School of Medicine, Changwon, Korea

²Department of Orthopedic Surgery, SNU Seoul Hospital, Seoul, Korea

³Department of Orthopaedic Surgery, Medical Research Institute, Pusan National University Hospital, Busan, Korea

Forearm replantation is a challenging procedure for both patients and medical professionals. High survival rates are now being achieved owing to developments in microsurgical techniques. However, patient expectations for a "functional hand" are ever-increasing. To obtain satisfactory functional results following major limb replantation, it is important to reduce the ischemic time. During forearm replantation, the time from the beginning of surgery to the anastomosis of the artery should be minimized. This step includes anesthesia, wound debridement, and bone fixation, which are key factors in choosing the most efficient method and reducing the time needed. Herein, we review the prognostic factors and report the general operative procedures for forearm replantation using our proposed surgical technique.

Keywords: Forearm, Upper extremity, Prostheses and implants, Replantation, Amputation

Introduction

The first replantation was performed in 1962 for amputation near the shoulder in a 12-year-old boy [1]. Since then, replantation techniques have continued to develop and improve. Currently, repair of vessels with a diameter as small as 1 mm is possible using super-microsurgery techniques, and replantation is performed for a wide range of injuries, including fingertip replantation and limb amputation. However, the surgical outcomes of upper-limb replantation have been unsatisfactory compared to those of digit replantation, which has led to doubts regarding the efficiency of upper-limb replantation surgeries [2-5].

Limb amputations are commonly accompanied by crushing injuries, leading to unsatisfactory replantation outcomes. However, patients demand better cosmetic and functional results than that associated with prostheses. Traumatic limb loss causes major functional deficits and is associated with negative psychological outcomes (including feelings of low self-esteem, loss of motivation, and negative quality of life). The objectives of upper- and lower-limb replantation should be discrete; lower-limb replantation is performed with the objective of helping patients walk without pain, which increases patient satisfaction related to functional recovery, in consideration of the high surgical costs. In a study involving below-the-knee amputations, satisfaction with functional recovery with the use of a prosthesis was higher than that in other cases [3,6,7]. With replantation of upper-limb amputation, functional and esthetic recovery is possible, and the satisfaction of those who experience replantation is higher than when implanting a less developed/premature electric prosthesis. An expensive electric prosthesis is not widely used in South Korea because of cost issues. It is also a highly modern-

ized design that does not sufficiently meet the patients' esthetic recovery requirements compared with the normal upper limb. Moreover, the multiple degrees of freedom and agility of the artificial limb are not comparable to those of the normal limb, especially with the current prosthetic technologies. Hence, the use of a prosthesis following upper-limb amputation can result in lower functional and psychological satisfaction outcomes [3,6-8].

Graham et al. [2] evaluated the functional outcomes of 22 successful upper-limb replantation cases performed near the wrist level. They compared the functional outcomes of amputated arms with those of replantation or prostheses and reported excellent outcomes of replantation. These results implied that a "bad hand" had higher functionality than that of a "good amputation" [8]. It is still questionable whether the recently performed arm re-transplantation is superior to the patient's safety and high surgical cost following immunosuppressive administration, ethical issues according to donor's choice, and the results compared to amputation with an appropriate implanted prosthesis devices [8]. Therefore, we suggest that surgeons perform replantation more aggressively in patients with upper-extremity amputation.

Traditionally, replantation of upper-limb amputation has focused on the survival rate. Current advances in technology, healthcare systems, and resources have shifted the focus to maximizing the surgical efficiency and functional outcomes of replantation [4,5,9,10]. This article discusses methods for achieving better outcomes of forearm replantation that are associated with a high frequency of upper-limb replantation.

Preoperative assessment of limb amputation patients in the emergency department

1. Life before limb

Medical professionals who assess patients with forearm amputation must be aware of the "life before limb" principle that unreasonable limb replantation can lead to patient death. Therefore, for patients in the emergency department, advanced trauma and life support systems, typically associated with traumatic injuries, should be provided. This helps identify accompanying injuries and diseases and, most importantly, maintains hemodynamic stability. This also helps determine the need for replantation while considering the ischemic time, degree of contamination, and severity of injuries. A tourniquet can be applied to amputated limbs to minimize blood loss; however, there is a risk of metabolic acidosis due to ischemic injury in the amputated part [11,12]. Once patients have achieved hemo-

dynamic stability, radiologic assessment is necessary, as well as an evaluation of whole-body status, age, occupation, and injury characteristics to determine the need for replantation surgery [11,12].

Replantation of forearm amputation

1. Objective

The goals of replantation are function preservation, independence of movement, and chronic pain prevention [12]. In particular, recovering protective sensations in the upper limb significantly affect patient satisfaction, increases the efficacy of rehabilitation, and promotes functional recovery of the digits. In addition, the recovery of nerves and muscles is necessary for the resumption of functional capacity. However, this is difficult to achieve. Surgeons and patients undergoing replantation of forearm amputation should be aware that the part of the limb being operated on will never be the same as the normal limb. This surgery was performed to improve functional, aesthetic, and psychological outcomes [13].

2. Surgical indications

Surgical indications for forearm replantation are similar to those for the replantation of an amputated digit. When deciding whether to perform replantation, the patient's age, injury mechanism, degree of injury, functional outcomes, and motivation for replantation should be considered before surgery [5]. Replantation cannot be performed for severely crushed or mangled injuries, multilevel amputation, prolonged normothermic ischemic time, or in cases of accompanying life-threatening injuries [14].

3. Prognostic indicators

Injury type

The mechanism of limb amputation injury is the most influential factor for survival and functional outcomes after replantation. Previous research found better outcomes in cut-type amputated digits compared to those in avulsion and crushing injuries [13], although it is difficult to compare results according to the mechanism of injury due to the small number of studies. Based on our experience, most forearm amputations are cases of avulsion amputations with crushing injuries, whose postoperative outcomes are unsatisfactory.

Ischemic time and degree

Ischemic time is an important factor for limb replantation. Unlike finger replantation, major limb replantation is significantly affected by the ischemic time in terms of postoperative

prognostic factors, which can confer a risk of injury-associated fatality in severe cases. In a few reported cases, the muscle mass was directly related to ischemic time [7,9]. Many successful cases of finger replantation 24 hours after injury have been reported, depending on the storage conditions of the amputated part [15]. Nonetheless, recovering blood circulation following limb replantation within 4 to 6 hours is vital for obtaining good outcomes [4,14]. For example, in amputation of the distal part of the forearm, revascularization should be performed within 6 hours after injury, and amputation in the proximal part of the forearm should recover circulation within 4 hours to obtain acceptable postoperative outcomes. To obtain a better prognosis, the operative time should be shortened to minimize the ischemic time and recover the maximum amount of muscle. Hence, experienced surgeons, who are familiar with the surgical procedures based on the time of arrival in the emergency room following an amputation accident, perform an initial assessment of patients, prepare for surgery, and transport patients to the surgery room to prevent delays and minimize ischemic time. Even if the amputated part is properly stored, core cooling of the extremity is insufficient to prevent muscle dysfunction. Therefore, circulation should be established by anastomosis of an artery in a short period of time.

During forearm replantation, the time from surgery onset to the anastomosis of the artery should be minimized. This includes the time needed for anesthesia administration, wound debridement, and bone fixation, which are key factors in choosing the most efficient method and reducing the time. Sabapathy et al. [7,14] aimed to complete bone fixation in 20 minutes by avoiding complex procedures and bone grafting. We agree with these principles and performed bone fixation within 30 minutes using a two-stage bone fixation method, which will be described later, with which a good result was obtained.

The guidelines followed during major replantation were adopted from Sabapathy et al. [7,14].

Other factors

1) Anticoagulation

In replantation, thrombosis may affect short-term outcomes. Most thromboses occur in the veins and are related to a low-flow state. Generally, low-dose aspirin or antiplatelet and antithrombotic treatments, such as intravenous (IV) heparin, low-molecular-weight heparin, dextran, and prostaglandin, are used postoperatively. Aspirin effectively reduces the occurrence of venous and arterial thrombosis with a low complication rate and is widely used [16].

No significant benefit was found with the administration of aspirin with other heparin-related products, including subcutaneous and IV heparin [16,17]. Administering IV heparin had no significant effect on the survival rate of the replanted parts [18]. After replantation, IV heparin is administered only occasionally for severely atherosclerotic vessels, unresectable intimal damage, and intraoperative thrombosis [18,19]. During vessel anastomosis, heparin irrigation reduces platelet aggregation and prevents arterial thrombus formation [19].

2) Smoking

Smoking impairs microcirculation in replanted digits [20]; however, its effect on the actual survival rate remains unknown [4]. Some reports have shown that smoking is related to the survival rate [21,22], while others have shown that smoking history does not affect replantation survival [23,24]. However, one of these studies reported that postoperative smoking negatively affected surgical outcomes [24]. Therefore, surgeons need to notify patients regarding the effect of smoking on limb replantation [4,9]. Other prognostic indicators of poor outcomes after replantation are shown in Table 1.

Operative procedures

1. Wound debridement and exploration

Debridement should be performed on the amputated limb. Contaminated tissues or foreign bodies should be removed as quickly as possible without interfering with function. Incisions should be made such that the anastomosis site remains covered at the end of all procedures. If the contamination level of the injuries is high, the major nerves and arteries should be tagged and debrided to minimize the loss of non-injured nerves or

Table 1. Prognostic indicators for poor outcomes after replantation

Prognostic indicators for poor outcomes after replantation
Crush/avulsion injury
"Red line" sign
Ribbon sign
Warm ischemia > 6 hours
Cold ischemia > 12 hours
Multilevel injury
Extensive bone loss
Nerve loss
Multiple joint disruption
Advanced age
Poor candidate for immobilization
Psychosocial disturbance
Rehabilitation compliance concerns

vessels [7,14].

During debridement, the small and minor vessels of the muscle should be thoroughly ligated to control bleeding after the tourniquet is released. Additional debridement is necessary after connecting the artery to reduce contamination after final replantation.

2. Bone shortening and fixation

Bone shortening is mandatory for the successful replantation of forearm amputations. When performing bone shortening, the goal is to perform primary repair of the blood vessels and nerves with minimal nerve grafts or vein grafts. This procedure relieves the strain on the artery to be repaired and prevents possible secondary conditions caused by the thrombus, such as arterial spasm and arterial insufficiency.

There is no literature on the maximum possible length that can be considered for shortening, but a 5 to 10-cm shortening in the upper extremity is possible. Because replantation should be performed within a short time, bone fixation using a simple method is preferred. Internal fixation is a technical option involving the use of a Kirschner-wire or plate, depending on the osteotomy site. In the case of a radioulnar fracture at a different site, one of the fractured bones can be fixed in a primary operation. Assessment of bone length, rotation, and congruency of the distal and proximal radioulnar joints of both the bones of the forearm using intraoperative and perioperative plain radiography is required. Radical debridement and periosteum-damaged bone fragments are removed because of bone shortening; so that, chances of nonunion can be low [25].

Author's surgical tip: As mentioned above, due to the delay in transferring patients to the hospital and preparing for surgery, debridement and arterial anastomosis after bone fixation should be completed within 2 hours. The bone fixation procedure should be simplified to reduce the duration of ischemia while providing sufficient fixation power for stable artery-to-artery anastomosis. The two-stage bone fixation technique was performed in two steps: (1) arterial anastomosis after bone fixation using a small plate by adding an external fixator; (2) then after 4 to 6 weeks, removing the external fixator with change of a long plate instead of a short plate. This method allowed for initial bone fixation within 30 minutes. During the first stage, we decided which bone to fix first, depending on the fracture severity in the radius and ulna. The length of the plate used during surgery was determined based on the length of the exposed bone after shortening. A long plate is useful for strengthening the fixation power for a better bone union. However, the amputated site should be dissected further, which

consumes more operative time and causes more tissue injury to the amputated part. The crushed or fractured bone was sawed vertically and a plate with four to six holes was fixed. Subsequently, the radius, ulna, and connecting arteries were serially fixed to ensure recovery of blood circulation. After replantation, external fixation was performed to ensure a strict bone fixation. The second operation is usually performed after 4 to 6 weeks. The external fixator was removed and replaced with a long plate, depending on the condition, or the previous plate was left as it was. In the case of bone defects, a bone graft was performed during the second operation. Based on our experience, using a short plate during the initial surgery shortened the fixation time and enabled a stable anastomosis. Even if this short plate cannot be replaced with a longer one, there is no problem in achieving bone union with good fixation power. This method can achieve revascularization within one hour after the induction of anesthesia (Fig. 1).

3. Vessel repair

The survival of the replanted arm depends on vessel anastomosis and maintenance of circulation. A technique involving vein repair can avoid venous stasis. In addition, a bloodless field should be created for an easier operation. However, in crushing or avulsion amputation, it is better to first connect the artery to find a suitable vein that functions well. At least one major artery should be repaired and connected to the maximum possible number of veins to reduce bleeding after release of the clamp. The comitant vein transfers a large amount of blood and should be restored as much as possible.

Author's surgical tip: There are two arterial reconstruction approaches; direct anastomosis and saphenous vein graft. We preferred direct anastomosis because of its shorter procedural time. A direct anastomosis usually connects the radial and ulnar arteries. In contrast, our researcher selected an approach wherein anastomosis of the radial and ulnar arteries was performed depending on the status of the vessel injuries. When these two arteries are cross-connected, the duration of the bone-shortening procedure can be further shortened.

Because the upper extremity does not require a lengthening procedure to match the length of both arms, proper bone shortening is the best way for artery anastomosis to reduce the ischemic time. After the arteries are connected and the blood circulation is recovered, vein repair is performed. Commitment venae flowing parallel to the artery should be connected as well as superficial veins in the skin, which can be injured by contamination or hemolysis. Therefore, every possible vein should be reconnected.

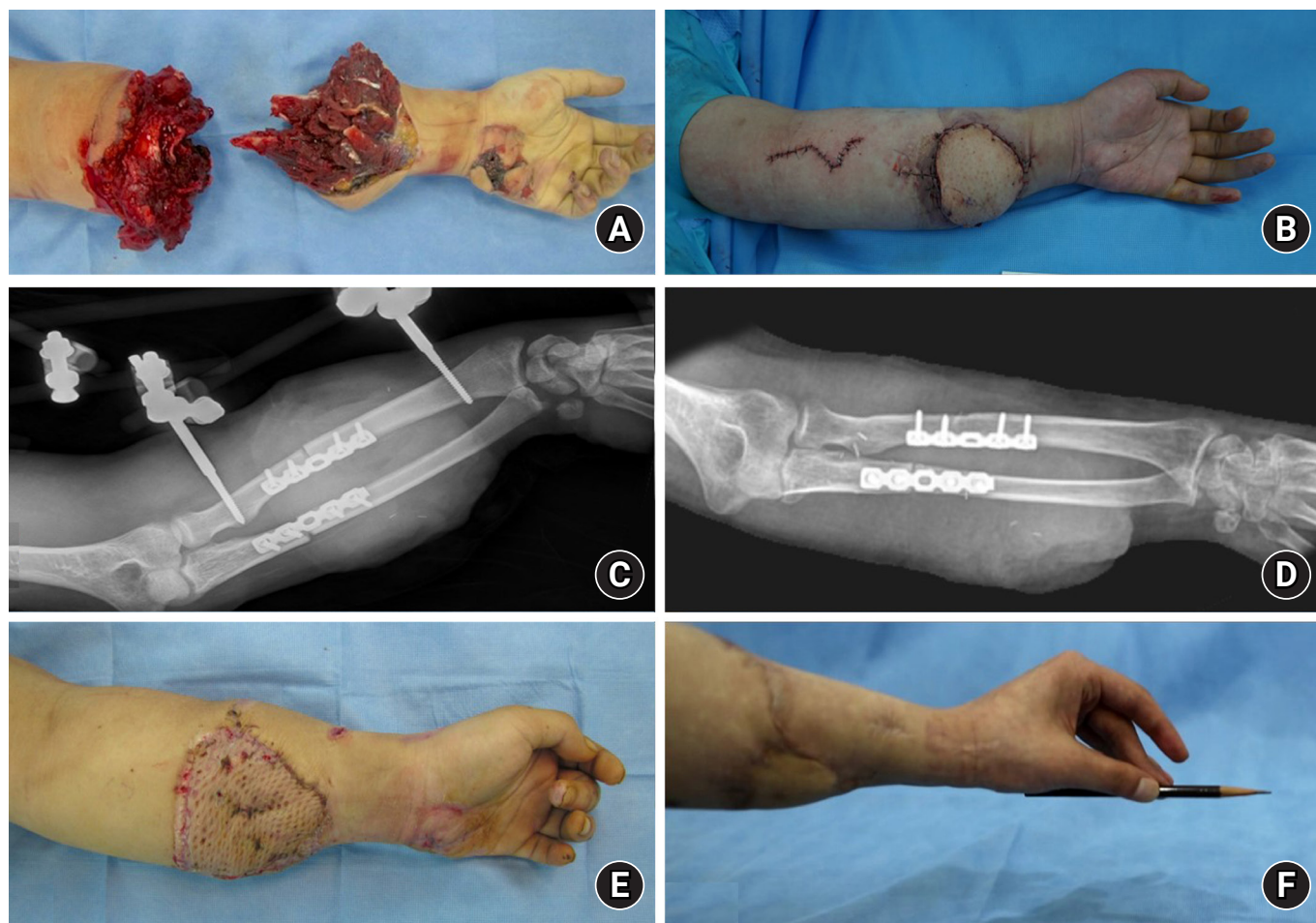


Fig. 1. Forearm amputation. (A) Photograph showing a 24-year-old male with an amputated forearm after a car accident. (B) We used a 5-hole reconstruction plate and external fixator for bone fixation during replantation surgery. It took 120 minutes from the start of the operation to artery anastomosis, and the total ischemia time was 7 hours. The time required for bone shortening and plate fixation was 30 minutes. (C) The external fixator was removed 6 weeks after surgery and followed by skin grafting. (D) For hand function, a free functional muscle graft using the gracilis muscle was performed 15 months after surgery. (E). Bone union was achieved without secondary bone fixation. (F) At the last follow-up at 19 months, Chen Grade II success (total range of motion, $\geq 60\%$; muscle strength, $\geq M4$; sensibility, ≥ 2 ; back to work) was observed. Written informed consent for publication of the clinical images was obtained from the patient.

4. Muscle and tendon repair

The tendon should be repaired during the initial surgery. As bone shortening is usually performed, primary tendon repair becomes easier. If possible, both the muscle belly and the epimysial repair should be sutured. In avulsion amputation, rupture frequently occurs at the musculotendinous junction. Even in this case, connecting the amputated tendon end to the proximal part of the muscle belly resulted in good functional outcomes. If there is a large defect, tendon transfer, tendon graft, or free muscle flap can be considered in the first or second stage.

Author's surgical tip: As the muscle of the amputated limb may be necrotic and increase the risk of infection, we decided

to remove the muscle as much as possible. The proximal muscle was used to cover the vessel-connected area to prevent damage. In addition, we chose the proximal muscle in good condition to connect the tendon of the amputated part with the flexor and extensor. We performed tenorrhaphy of the 2nd through 5th finger flexors together and tenorrhaphy of the thumb separately. The entire extensor is connected to the muscle once.

5. Nerve repair

It is preferable to perform neurorrhaphy of the major nerves during the primary repair without a nerve graft. Bone shortening was performed to avoid nerve graft. If primary repair is not

possible, the nerve should be tagged in the appropriate area to ease operation of the nerve graft.

Skin cover

Additional debridement can lead to skin or soft-tissue defects. A skin graft can be performed if there is a good muscle bed and blood vessels, tendons, bones, and plates are not exposed. A vacuum-assisted device (VAC) can temporarily protect the injured part and help achieve successful secondary reconstruction. The VAC should avoid vessel anastomosis and apply a low vacuum of 70 mmHg.

Fasciotomy

If the duration of cold and warm ischemia exceeds 6 hours or in cases of crushing amputation, a fasciotomy should be performed. Before performing the fasciotomy, the overall condition should be assessed for tension or hardness in the affected limb following surgery.

Postoperative monitoring and care

The risk of thrombosis until postoperative day 2 increased to 80%, and then decreased by 10% on postoperative day 3 [7]. However, no commonly accepted anticoagulation protocol is available, and antithrombotic treatment is widely used postoperatively. Intraoperative heparinized saline irrigation was recommended. Alternatively, heparinized saline irrigation should be performed before releasing the clamp, and a 50–100 IU/kg of heparin bolus should be injected. Following surgery, a continuous IV infusion of a combination of 5,000-IU heparin and 500-mL saline was recommended. Otherwise, 0.4 mL/kg/hr dextran can be administered until postoperative day 5, or chlorpromazine with a sedative can be infused for peripheral vasodilation [7]. Importantly, aspirin was prescribed for postoperative 3 to 4 weeks. However, the use of antithrombotic drugs has not been reported to increase survival rates [4].

For the early detection of arterial and vein thrombosis in the anastomosis area, the junction should be monitored. Temperature-probe transcutaneous sensors and laser Doppler flowmetry are useful for detecting arterial or venous thrombi. Doppler ultrasonography is another useful modality for visualizing blood flow and detecting dynamic changes in tissues. However, such systems are complex and uncommon. The most important aspect is clinical assessment. The color of the fingertips should be compared with that of normal fingers. In general, a pale fingertip indicates arterial compromise and a blue/purple color change of fingertip implies venous congestion. Urine output and continuous electrocardiogram monitoring are neces-

sary for massive hemorrhages. Hemoglobin and electrolyte levels should also be periodically measured and corrected [14].

Secondary surgery

For forearm replantation, good functional results are seldom achieved. Most patients require secondary surgery for soft-tissue contractures, joint stiffness, and malunion or nonunion [26]. Furthermore, tendon transfer, selective arthrodesis, and soft-tissue augmentation or scar correction, including flaps, are required to improve the functional defects caused by failure of tenorrhaphy or neurorrhaphy. Splinting and physical therapy are required to treat the joint stiffness. Secondary surgery is not necessary for the first web space release or capsulotomy because the splint is replaced periodically, and the fingers are corrected. Secondary surgery can be scheduled after evaluation of rehabilitation status, soft-tissue condition, and overall physical condition. Three months after the first surgery, a secondary surgery for the nerves and tendons can be performed. Additionally, a tourniquet can be used in the amputated limb, depending on the condition of the soft tissue to be opened, although its safety outcomes remain unproven. Tagging or charting the location of the tendons and nerves during the initial surgery should be useful in reducing the dissected area during the secondary surgery.

Difference between forearm replantation and major limb replantation

For anatomical reasons, a lower success rate and worse functional outcomes have been reported in association with proxi-

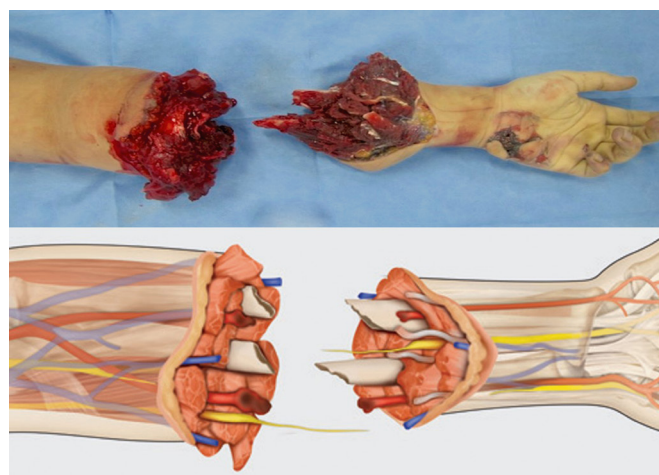


Fig. 2. Forearm amputation.

mal amputation of the forearm [27]. Forearm amputation following an avulsion injury is associated with tearing such as crushing, twisting, and bending injuries. These injury patterns are discontinuous and unpredictable with respect to the area of injured tissue and the degree of injury [28] (Fig. 2).

The 20 muscles of the proximal forearm are innervated by most blood vessels and motor nerves, which are usually within 10 cm of the cubital crease. If amputation occurs in these areas, the nerves and vessels of the injured part must be anastomosed or transplanted, and ischemic or crushed muscles can cause contamination or fibrosis. Fibrous scar tissue and large-area nerve injuries cause muscle dysfunction and poor recovery of distal sensations [28].

Functional assessment and outcomes of forearm replantation

Survival rates of 74% to 100% have been reported for patients with upper-limb replantation, and only a few studies have discussed the outcomes of major upper-extremity replantation at the proximal area of the wrist. Some studies published after 2000 reported survival rates of 94% to 100% for major upper-extremity replantation [10,16,28-30].

However, as mentioned earlier, functional assessment of upper-extremity replantation is vital. Chen's criteria were used to assess the surgical outcomes of upper-extremity replantation [31,32]. These criteria evaluate functionality in four aspects: (1) ability to work, (2) range of joint motion, (3) recovery of sensation, and (4) muscle power [32]. Grades I (excellent) and II (good) indicate good functionality, grade III indicates fair functionality, and grade IV indicates poor functionality.

Previous studies reported contrasting findings regarding the injury mechanism of the functional limb; Chen grade I or II was reported in >30% of cases after replantation of the proximal arm [28,33]. In relatively recent studies on upper-extremity replantation, high grades were reported in 40% to 77.7% of cases of significant functional impairment [5,10,34-36]. Despite poor functionality, patients reported higher satisfaction scores; these inconsistencies were explained by emotional factors, such as preservation of integrity with respect to body image [28].

Recently, the Disabilities of the Arm, Shoulder, and Hand Questionnaire (DASH) or the Michigan Hand Outcome Questionnaire (MHQ) has been commonly used for patient-reported outcome measures [36]. These questionnaires can be used for the assessment of hand functionality and symptoms. The MHQ is a commonly used outcome evaluation questionnaire for hand surgery, based on symptoms, functionality, aesthetics, and pa-

tient satisfaction [37]. These tools evaluate the surgical outcomes of hand disabilities with high credibility and validity [38].

Conclusions

Functional recovery is the main goal following amputated forearm replantation and can be achieved by shortening the ischemic time until arterial anastomosis. The factors affecting ischemic time include patient transport time after amputation, preparation for surgery by the professional surgical team, and bone fixation time for the amputated part during surgery.

During forearm amputation replantation, the time from the injury to anastomosis of the artery should be minimized. Surgeons need to focus on reducing the time by selecting the most efficient methods for wound debridement and bone fixation before vascular anastomosis.

ORCID

Dong Hee Kim, <https://orcid.org/0000-0003-4358-9356>

Sang Ho Kwak, <https://orcid.org/0000-0002-5634-5716>

Sang Hyun Lee, <https://orcid.org/0000-0002-2084-9824>

Conflicts of interest

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