Microvascular Reconstruction in Burn and Electrical Burn Injuries of the Severely Traumatized Upper Extremity

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Background: As the versatility and variability of free flaps have significantly increased during recent years, so have the indications for free tissue transplantation in burn reconstruction expanded.
Methods: The authors report retrospectively the results of 42 free flaps for upper extremity reconstruction in 35 severely burned patients using 13 different free flaps. This experience enabled the authors to establish reconstructive principles pertinent to the type of injury (burn versus high-voltage injuries) and the timing of reconstruction procedures.
Results: In high-voltage injuries ($n = 17$), early free flap coverage with muscular flaps was the most frequently used type of reconstruction. The reconstruction site was predominately the forearm. In burn injuries, free flap coverage was performed during a later stage of the treatment course. Reconstruction with cutaneous or fascial flaps was the preferred method. The elbow and dorsum of the hand underwent defect coverage in most circumstances. For reconstruction of complex or large defects ($n = 6$), combined "chimeric" flaps were used. Overall, the flap failure rate was 12 percent ($n = 5$). Interestingly, there was a relationship between flap failure rate and timing of the procedure. Four of five flap failures occurred within 5 to 21 days after trauma, and all five flap failures occurred between 5 days and 6 weeks. No flap failure occurred during secondary reconstruction.
Conclusions: The authors' data demonstrate that burn and high-voltage injuries are distinct entities, each requiring custom-tailored reconstructive solutions for limb salvage. Even if the authors' flap failures all occurred during the first 6 weeks, it should not be forgotten that this type of coverage is the only alternative to amputation in selected cases. (*Plast. Reconstr. Surg.* 119: 605, 2007.)

The progress of microvascular free tissue transplantation in recent decades has led to an increasing use of free flaps for reconstruction in burn patients,[1,2] and the flaps have reached a high level of sophistication. Fascial flaps,[3] preexpanded flaps,[4,5] composite tissue flaps, multiple flap transplantations in the same patient, and combined flaps ("chimeric" flaps) based on a single pedicle have been performed in patients with more severe burns and larger defects of the upper extremities.[6] The purpose of this article is to provide principles for decision-making in microvascular burn reconstruction for salvage of the upper extremities, particularly with regard to the type of injury and the timing for free flap coverage.

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PATIENTS AND METHODS

Between July of 1994 and June of 2003, a total of 42 free flaps were performed in 35 burn patients with severely traumatized upper extremities. Patients with a combined crush/burn injury or with a Marjolin ulcer secondary to old burn scars were not included in the study. Patient data were analyzed retrospectively. Each patient chart was reviewed for age and gender, type of injury, indication for a free tissue transfer, timing of the reconstructive procedure, complications, final outcome, and success rate. The timing of the free flap after trauma was classified into two major categories: primary reconstruction and secondary reconstruction. Primary reconstruction comprised three subgroups: immediate (<5 days), early (within 5 to 21 days), and intermediate (within 21 days and 6 weeks) treatment groups. Late or secondary reconstruction included all free flaps performed 6 weeks or more after injury. An unsatisfactory primary closure of the defect had already been attempted in most cases. The flap failure rate was analyzed in relation to the timing of the operation and in relation to the type of injury (high-voltage injury versus burn injury, comprising contact burns, flames, or fluid burns).

RESULTS

Forty-two free flaps were performed in 35 patients. The average age of the nine women and 26 men was 35 years (range, 7 to 75 years). The cause of the defect or deformity was a high-voltage injury in 17 cases and a full-thickness burn injury in 25 cases (Table 1). The average total body surface area burned in the latter group was 28 percent, ranging from small contact burns of 1 percent up to a burn of 78 percent of total body surface area.

Thirteen different types of free flaps were used (Table 2). Combined flaps with at least two components based on one pedicle (chimeric flap) were performed in five cases (two combined latissimus/serratus flaps and three combined parascapular/scapular flaps). Overall, 50 percent of the free flaps (n = 21) were performed primarily (<6 weeks) and 50 percent of the procedures were secondary reconstructions (>6 weeks). The type of free flap most frequently used varied according to the timing of the procedure (primary versus secondary) (Table 2).

For primary reconstruction, pure muscular free flaps (latissimus dorsi, gracilis, and combined latissimus/serratus) were predominantly used (n = 10). Flaps with a cutaneous component (tensor fasciae latae, parascapular, radial forearm, lateral arm, and combined parascapular/scapular) were used in nine cases. Combined flaps (latissimus/serratus and parascapular/scapular) for large defects were used in 19 percent (n = 4). For secondary reconstruction, eight flaps were pure muscular flaps (latissimus dorsi and gracilis), whereas the majority of free flaps (n = 10) were cutaneous flaps (tensor fasciae latae, parascapular, and combined parascapular/scapular). During secondary reconstruction, only one free flap was a combined flap (parascapular/scapular).

Table 1. Patient Profiles, Cause of the Burn Injury, and Number of Free Flaps Used

Study Population	Value (%)
Total no. of patients	35
No. of female patients	9
No. of male patients	26
Age, years	
Average	35
Range	7–75
No. of free flaps	42
Cause of injury	
High-voltage	17 (40)
Burn	25 (60)
Timing	
Primary (<6 weeks)	21 (50)
Secondary	21 (50)

Electrical Burn/High-Voltage Injury (n = 17)

Site

In this etiologic group, limb salvage was the sole cause of free flap coverage. Seventeen free flaps were used for upper limb reconstruction, predominantly for purposes of forearm reconstruction (n = 11). The proximal extremity was rarely involved (Fig. 1).

Timing

In the high-voltage group, most free flaps [n = 11 (65 percent)] were performed for primary reconstruction. One free flap was used for immediate reconstruction (<5 days), nine for early reconstruction (5 to 21 days), and one for intermediate reconstruction (3 to 6 weeks). Six free flaps were performed as secondary reconstructions (Figs. 2 through 4).

Type of Free Flap

Eight flaps (47 percent) were pure muscle flaps (latissimus dorsi and combined latissimus/serratus), whereas nine flaps (53 percent) were cutaneous flaps (tensor fasciae latae, parascapular, radial forearm, and combined parascapular) (Table 2).

Burn Injuries (n = 25)

Site

In upper limb reconstruction, free flaps were performed mainly to the elbow (n = 9) and the dorsum of the hand and fingers (n = 8) (Fig. 1).

Timing

Compared with the electrical injury group, flaps were performed later in the course of treatment. More than half of the free flaps [n = 15 (60 percent)] were carried out for secondary recon-

Table 2. Type of Free Flaps Used in All Patients, in Burn or High-Voltage Injuries, for Primary or Secondary Reconstruction

	Type of Free Flap				
	All (n = 42)	Burn (n = 25)	High-Voltage (n = 17)	Primary (n = 21)	Secondary (n = 21)
Muscle flaps (n = 18)					
Latissimus dorsi	11	4	7	7	4
Gracilis	5	5	0	1	4
Combined latissimus/serratus	2	1	1	2	0
Musculocutaneous flaps (n = 5)					
Tensor fasciae latae	5	2	3	2	3
Adipocutaneous flaps (n = 14)					
Parascapular	7	3	4	2	5
Preexpanded	1	1			1
Radial forearm	1		1	1	
Perforator	1	1		1	
Lateral arm	1	1		1	
Combined parascapular/scapular	3	2	1	2	1
Bone flaps (n = 1)					
Free fibula	1		1		1
Fascial flaps (n = 4)					
Serratus fascia	3	3		2	1
Temporoparietal fascia	1	1			1

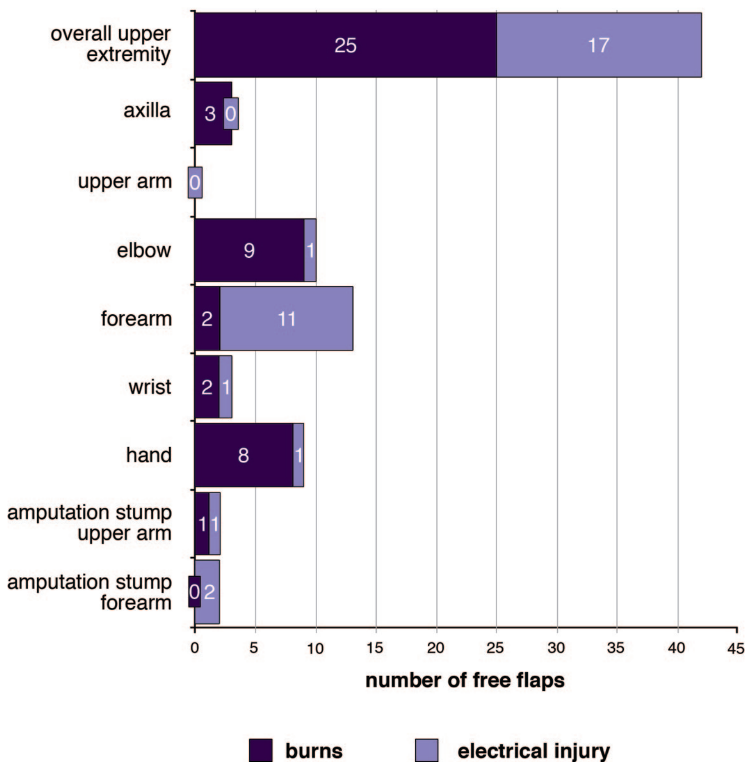

Fig. 1. Area of free flap reconstruction in the upper extremity. A differentiation is made between reconstruction after burn and electrical injuries. Several free flaps were used to cover amputation stumps.

struction purposes and 10 free flaps (40 percent) were carried out for primary reconstruction. Of these 10, one was used for immediate (<5 days), two for early (5 to 21 days), and seven for intermediate (3 to 6 weeks) reconstruction (Fig. 2).

Type of Free Flap

Ten flaps (40 percent) were cutaneous flaps [tensor fasciae latae (Fig. 5), parascapular, radial forearm, lateral arm, and combined parascapular/scapular] and four flaps (16 percent) were

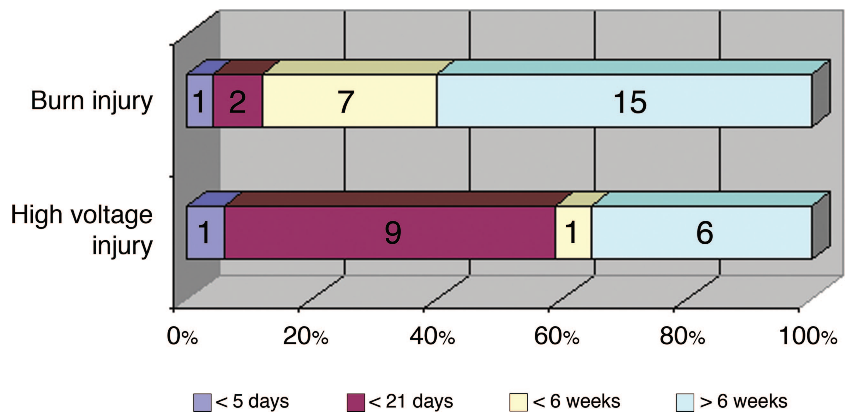

Fig. 2. The timing of the microvascular procedure is shown in the burn and high-voltage groups. Primary reconstruction includes an immediate (within 5 days), early (5 to 21 days), and intermediate (within 21 days and 6 weeks) period after trauma. Secondary reconstruction was performed later than 6 weeks after trauma.

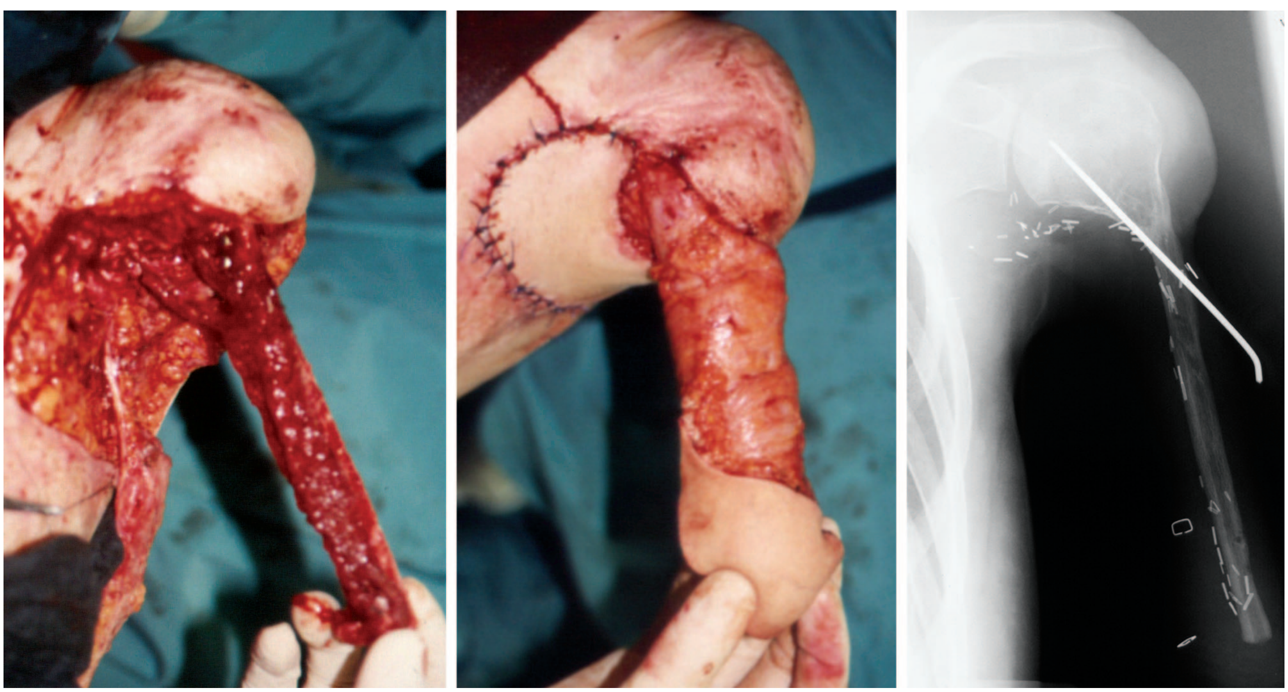

Fig. 3. A 14-year-old girl with a total body surface area burn of 43 percent after a high-voltage injury. The left arm had to be amputated early in another hospital. The amputation stump was too short for the fitting of a prosthesis and therefore was lengthened by transplantation of a free osteocutaneous fibula flap on the proximal stump of the humerus (*left*). For defect coverage, a pedicled latissimus dorsi flap was used (*center*). Republished by permission of Springer-Verlag, Heidelberg, Germany, from Baumeister, S., Germann, G., Geissler, G., Dragu, A., and Sauerbier, M. Reconstruction of burned extremities by free flap transplantation. *Chirurg* 75: 568, 2004.

fascial flaps [serratus (Figs. 6 and 7) and temporoparietal] (Table 2).

Complications

No intraoperative deaths occurred. The flap survival rate was 88 percent. Overall, there were five flap failures, with complete necrosis in four patients. In three patients, amputation was necessary as a result of flap failure. After removal of the failed flaps, the remaining defect could be closed with a skin graft in one case (Table 3). All of the cases were situations where amputation was the only alternative to attempting to salvage the extremity.

The relationship between the timing of reconstruction and flap survival rate is shown in Figure

Fig. 4. Same patient as shown in Figure 4. Results without prosthesis 1 year after operation (*above*) and with prosthesis for a better aesthetic appearance (*below*). Republished by permission of Springer-Verlag, Heidelberg, Germany, from Baumeister, S., Germann, G., Geissler, G., Dragu, A., and Sauerbier, M. Reconstruction of burned extremities by free flap transplantation. *Chirurg* 75: 568, 2004.

8. All flaps survived when the procedure was performed either immediately (within 5 days) or at a later stage (>6 weeks after trauma). Eighty percent ($n = 4$) of the failed flaps were performed within 5 to 21 days after trauma. All failures occurred when the flap was performed within 6 weeks after the trauma (Fig. 8).

The impact of the type of injury on the survival rate of flaps is shown in Figure 9. The survival rate was lower in the high-voltage injury group than in the burn injury group (76 percent versus 96 percent) (Fig. 9).

Complications at the recipient site of the flap were two hematomas and one infection requiring revisions. In five cases, additional skin transplantation was necessary because of harvesting large combined flaps from the subscapular system. One arterial and one venous revision were successfully carried out. Complications as mentioned above ($n = 10$) occurred more often in primary reconstruction ($n = 6$) and after high-voltage injury ($n = 7$).

DISCUSSION

Platt et al. reported that a free flap transplantation was performed in only 1.5 percent of all surgically treated burn patients.[7] The first data concerning free flaps in burn injuries were published by Sharzer et al. and Harii et al. in 1975.[2,8] Since that time, numerous applications of various free flaps have been reported. Initially, microsurgery was used only for secondary burn reconstruction.[1,9] As the field of microsurgery expanded rapidly, two main developments in burn reconstruction can be noted when reviewing the literature:

1. Indications, versatility, variability, and complexity of free flaps have increased markedly, so that free tissue transplantations are more often used in acute reconstruction[10] and for coverage of larger and complex tissue defects.
2. Larger patient series have been published that have permitted the development of reconstructive principles.[9–13]

Fig. 5. This patient had suffered from a burn injury of 65 percent of the total body surface area and presented a contracture of the shoulder area caused by scars in the right axilla (*above*). These scars were removed and the axilla was reconstructed by means of a free tensor fasciae latae flap. The early functional result demonstrates a reasonable shoulder abduction (*below*).

Fig. 6. This 22-year-old man sustained a total body surface area burn of 15 percent after a gas explosion.

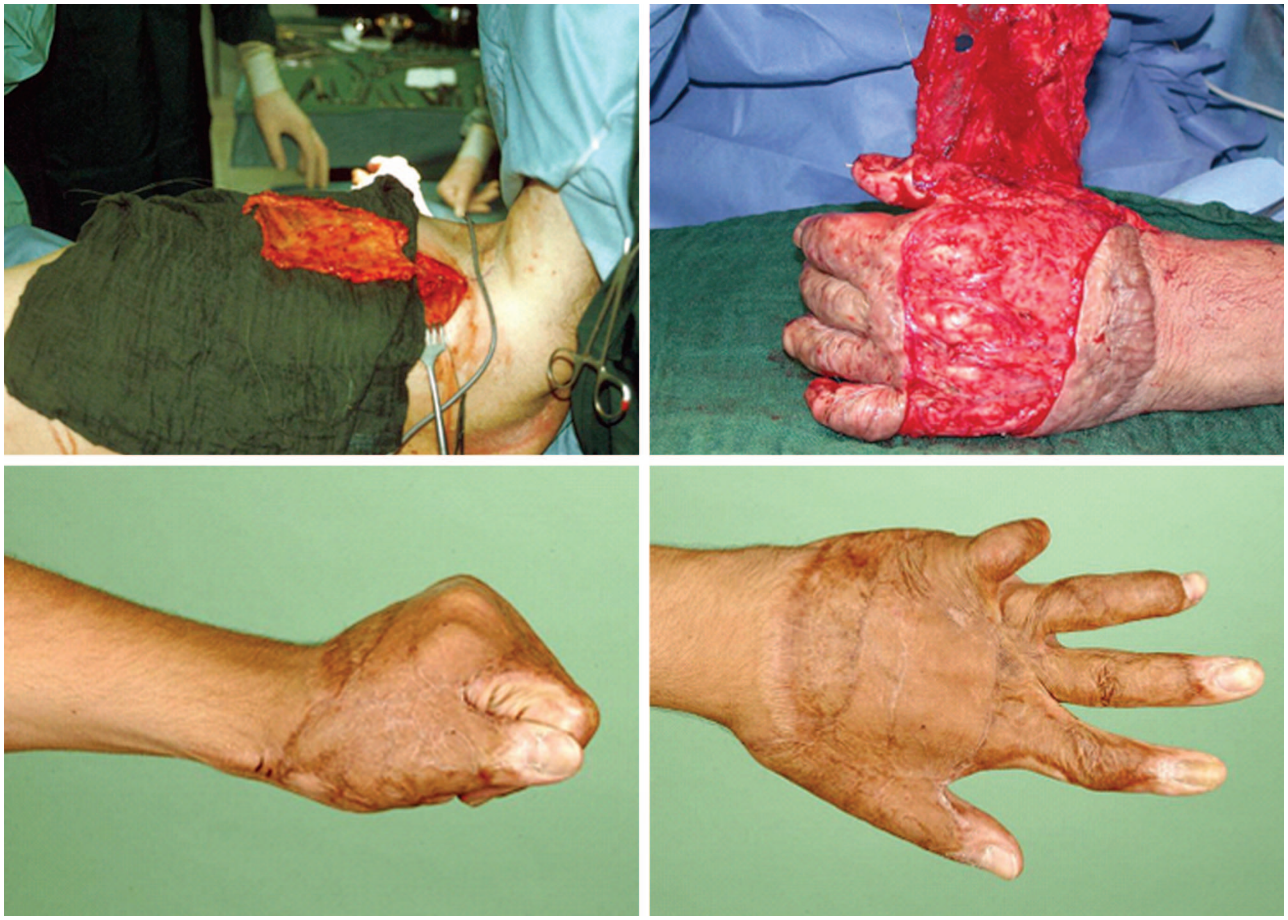

Fig. 7. Same patient as shown in Figure 6. After contracture release and scar removal of the left hand a free serratus fascia flap was transplanted (*above*). The functional and aesthetic results after operation are very satisfactory (*below*).

Table 3. Flap Failures and Surgical Consequences of the Study

Patient	Age (yr)	Sex	Injury (TBSA %)	Site	Free Flap	Timing	Reason for Failure	Salvage Procedure
1	50	Male	High-voltage (16)	Forearm	Latissimus dorsi; tensor fasciae latae	5–21 days	Sepsis, thrombosis	Upper arm amputation
2	31	Male	Burn (47)	Dorsum of the hand	Lateral arm flap	21 days–6 wk	Arterial thrombosis	Split-thickness skin graft
3	45	Male	High-voltage (10)	Forearm	Latissimus dorsi	5–21 days	Arterial thrombosis	Upper arm amputation
4	34	Male	High-voltage (24)	Forearm	Latissimus dorsi	5–21 days	Arterial thrombosis	Forearm amputation

To our knowledge, the presented data constitute the largest series of free flaps used for reconstruction of burn injuries in the upper extremity. This enabled us to differentiate between burn and high-voltage injuries and to highlight reconstructive principles based on the mechanism and pattern of injury of both entities.

In high-voltage injuries (>1000 V), the point of entrance of the electrical current is usually located on the distal extremity. Tissue destruction decreases from distal to proximal. This is apparent, with our data showing more free flaps to the distal (wrist) than to the proximal (axilla) extremity. In the forearm, it was shown by Zelt et al. that specific regions or "choke points" existed such as the wrist and elbow, where decreased cross-sectional areas and highly resistant tissue composition (tendinous and bony configuration) resulted

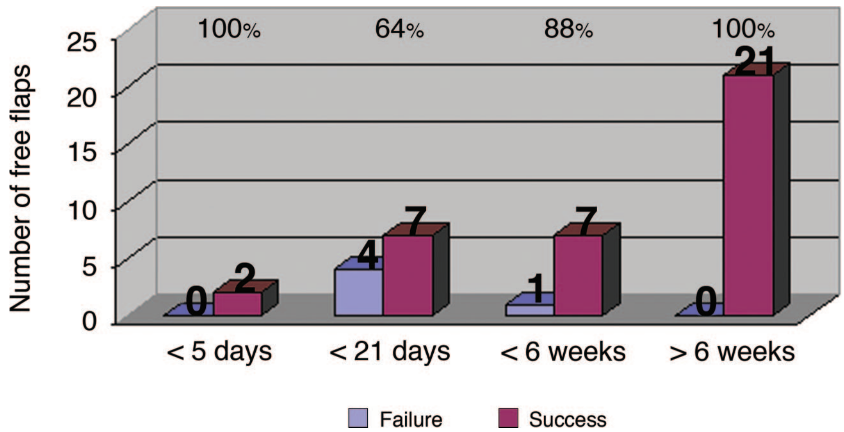

Fig. 8. Success rate (percentage) of free flaps with regard to the timing of the procedure. Four different reconstructive periods are shown. Primary reconstruction includes an immediate (within 5 days), early (5 to 21 days), and intermediate (21 days to 6 weeks) period after trauma. Secondary reconstruction was performed at least 6 weeks after trauma.

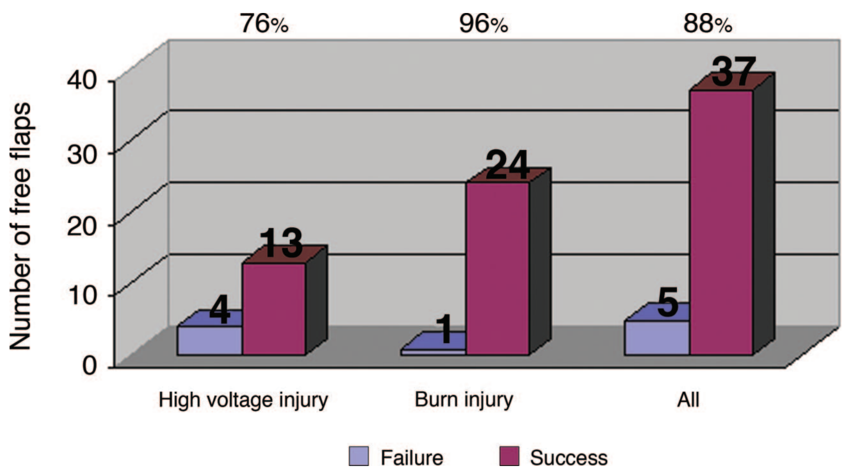

Fig. 9. Success rate (percentage) of free flaps in the entire group and with regard to the type of injury (burn/high-voltage injury).

in increased heat production and more severe tissue damage.[14] However, in our series, the predominant area of reconstruction was the forearm ($n = 11$). The critical choke point areas were not often involved in free flap coverage, with only one flap each to the wrist and elbow (Fig. 1). The deep muscle damage therefore would appear to determine the site of reconstruction more than the choke points. In addition, free flaps in electrical injuries were more commonly used early (within 5 to 21 days) in the posttraumatic course (53 percent) in contrast to burn injuries (8 percent).

Site and timing of reconstruction markedly influenced the type of free flap used. The indication for a free flap early after trauma is limb salvage with coverage of exposed functionally important structures such as vessels, nerves, tendons, and bones. In addition, the risk of an impending infection is high during this period. This explains the predominant use of muscle flaps for primary salvage (Table 2). They provide excellent perfusion and may reduce the risk of wound infection.[15] For large defects, the latissimus dorsi flap with a size of up to 33 cm length in a man and 26 cm in a woman[16] or chimeric flaps from the subscapular system[6,17] were most commonly used. For smaller defects, the gracilis muscle can be an alternative.

In burn injuries, in contrast, the most common sites for free flap coverage in the upper extremity were areas with a thin overlying protecting soft tissue such as the dorsum of the hand and fingers (Figs. 6 and 7), and the wrist and elbow

(Fig. 1). Timing also differed in comparison with high-voltage injuries. First, free flaps after burns were used later in the acute treatment. Second, in accordance with the literature, secondary reconstruction was much more common in the burn group (60 percent) than in the high-voltage group (35 percent) (Fig. 2), because of aesthetic and functional corrections of joint contractures (Fig. 5) and unstable scars.[1,11,12,18]

Once again, the site and timing of reconstruction influenced the type of free flap used. For reconstruction of the dorsum of the hand, fascial flaps provide thin, pliable coverage. For larger defects, the serratus fascia is the flap of choice; for smaller defects, the temporoparietal fascial flap is preferred.[19] An alternative could be thin subdermal plexus–based flaps, which are an ideal choice for contour-sensitive areas including hand scars.[20] This could supplant fascial flaps, which always require a skin graft, which can become an aesthetic compromise.

In secondary reconstruction, cutaneous flaps were used in 48 percent compared with 43 percent for primary reconstruction (Table 2). Adipocutaneous (parascapular/scapular) or musculocutaneous flaps (transverse rectus abdominis musculocutaneous/tensor fasciae latae) provide elastic skin, give better contour, and are therefore preferred for release of contracted joints and correction of aesthetic deformities.

Complications

When discussing the safety of microsurgical procedures in burn and electrical injuries, two questions need to be addressed: first, is the survival rate of free flaps dependent on the timing of the procedure (primary versus secondary)? Second, is it dependent on the type of injury (burn versus high voltage injury)? With regard to the latter, the flap failure rate in the burn group was 4 percent compared with 24 percent in the electrical injury group, and 24 percent in all primary reconstructions. Literature data concerning comparisons of flap failures in burn reconstruction are sparse. Unfortunately, a clear differentiation between burn and electrical injury or between primary or secondary reconstruction is made rarely. For acute free flap reconstruction, only Shen et al. provide data on a larger patient group of 54 cases.[10] The overall failure rate in this study was 17 percent, but they did not differentiate between burn and electrical injuries. De Lorenzi et al. reported on 39 free flaps, with a failure rate of 8 percent, but almost all free flaps ($n = 35$) were used for secondary reconstruction.[12] Abramson et al. reported on 45 flaps for secondary reconstruction, with a failure rate of 4 percent.[11] We had no failures in the secondary reconstruction group.

The effect of reconstructive timing on flap failure is obvious (Fig. 8). The failure rate was 24 percent in primary reconstruction and 0 percent in secondary reconstruction. Most flap failures occurred during the time period 5 to 21 days after injury (80 percent). All flap failures occurred when performed between 5 days and 6 weeks after trauma. From the literature concerning the period after trauma, it is known that the complication and necrosis rate of flaps increases when reconstruction is performed later than 5 days. Likely causes are an increased infection rate at the recipient site, intravascular thrombogenicity,[21] or a posttraumatic vascular damage.

Attempting to avoid this high-risk period by performing a free flap earlier than 5 days after trauma is often difficult, because of cardiovascular instability in the severely burned patient or because the need for a free flap has not become apparent at such an early stage. Even authors who favor early free flap coverage performed only four of nine flaps earlier than the fifth day postburn.[22]

The failure rate in the electrical injury group (24 percent) was higher than in the burn group (4 percent). The safety of microsurgical procedures in electrical injuries is controversial. Vascular abnormalities such as damage to media and endothelium,[23] vascular occlusions,[24] arteritis and aneurysm formation,[25] thrombosis and segmental narrowing of major extremity vessels, and a marked decrease in the density of small nutrient vessels have all been described after electrical injuries.[14] However, the clinical impact of these observations is not clear and, despite vascular injury, free flaps may be performed safely if the vascular anastomosis can be performed remote from the area of necrosis. In an experimental study, Kuo showed that free flaps could be performed safely in electrical injuries in rabbit limbs. He stated that blood vessels 3 cm beyond the margin of the wound can be used when inspected for normal elasticity, intact endothelium, and good bleeding.[26] Shen et al. claimed that the most reliable indicator for patency and useful vessels is intraoperative inspection under the microscope.[10] The same is probably true for burns with pure thermal injuries, because whether the vascular damage encountered in electrical injuries might be caused primarily by heat and not related specifically to electricity is controverisal.[27] This is supported by the fact that vascular lesions have also been described after thermal injuries alone.[10]

In summary, we encountered a lower failure rate in the burn group compared with the electrical injury group. However, as more free flaps in the electrical injury group were performed early after trauma, this seems to be more likely attributable to the timing of the procedure than to specific thermally or electrically caused vascular damage. Having excluded the effect of timing, there is no evidence to suggest, either from our data or from the literature, that there is a difference in the safety of microsurgical procedures between burn and electrical injuries.

However, the reconstructive principles for upper limb salvage as set out merely provide guidelines (Fig. 10). Our series of 42 free flaps with 13 different free flaps clearly demonstrates the complexity of burn reconstruction. The variability of the defect site, size, and depth draw on the entire plastic surgical repertoire. Furthermore, possible donor sites of first-choice free flaps might be burned as well, so the reconstructive surgeon needs to retreat to second- and third-choice flaps.

A particular challenge is posed by either compound or very large defects, which are hardly mentioned in the literature. These defects require composite tissue free flaps or several free flaps either on one (chimeric) or several pedicles. For extensive defects, the subscapular system provides a huge variety of free flaps.[6,28] The subscapular system served as a donor site for five chimeric or composite flaps (Table 2). Defects of up to 60 cm length or combined soft-tissue and bone defects could be covered.

In secondary reconstruction, a further option to cover larger defects is the expansion of free flaps.[5,9,29] Expansion can be performed before and after flap transplantation. The advantage is not only an increase in flap size but also the primary thinning of the transplanted tissue.[8,14]

Of course, flap alternatives such as perforator flaps should be mentioned as a possibility for defect coverage. However, the use of those flaps in such severe injuries could be restricted because of the need for solid vessels and a short operation time.

CONCLUSIONS

Overall, even in severe, life-threatening burn injuries or high-voltage injuries, the relatively long operation time was tolerated in all cases. No

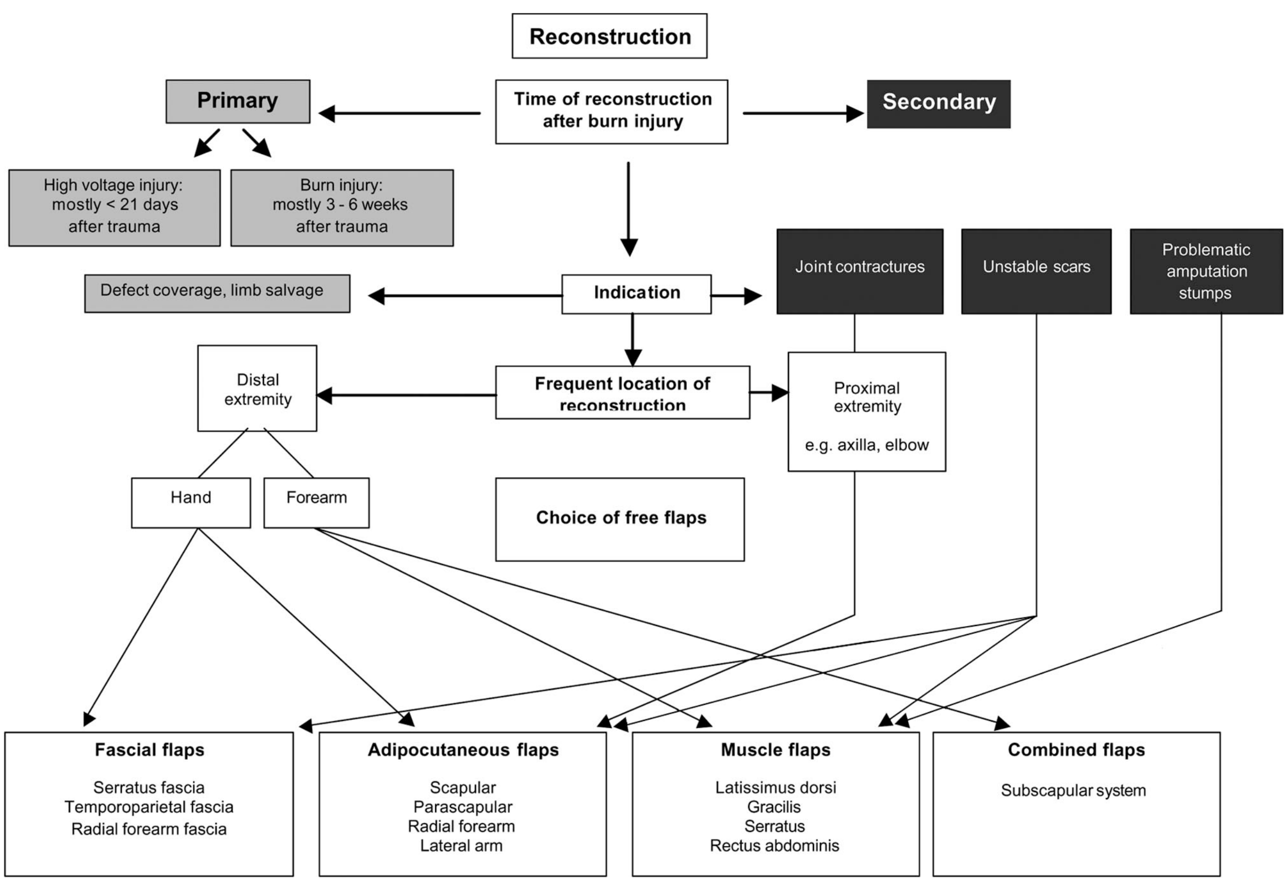

Fig. 10. Algorithm for decision-making between primary and secondary upper extremity reconstruction.

deaths occurred intraoperatively. Although the complication rate in primary reconstruction is slightly higher than in the secondary reconstruction period, the data demonstrate that complex microvascular reconstructive procedures are worthwhile for upper limb salvage. In secondary reconstruction, it has become a method of first choice, because complication rates are comparable to those of other elective reconstructions, and functional and aesthetic results are excellent.

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DISCLOSURE

None of the authors has a financial interest in any of the products, devices, or drugs mentioned in this article.

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