Timing and Outcomes of Free Flap Reconstruction in High-Voltage Electrical Burns of the Extremities

A Retrospective Study

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Background: High-voltage electrical burns of the extremities often result in deep tissue destruction with exposure of vital structures, necessitating free flap reconstruction. However, the optimal timing for reconstruction remains uncertain, particularly in the presence of evolving tissue viability.

Methods: This retrospective study included 23 patients with full-thickness high-voltage electrical burns involving the extremities who underwent free flap reconstruction. Patients were divided into two groups based on timing of flap coverage: early (<21 days) and delayed (>21 days, after at least 2 debridements). Outcomes assessed included flap survival, complications, reexploration rate, operative time, and hospital stay.

Results: The cohort was predominantly male (male-to-female ratio of 10:1) with an age range of 15 to 60 years. The upper limb was involved in 16 patients; and the lower limb, in 7. The overall flap survival rate was 87% (20/23). Flap failure occurred in 1 of 6 early cases and 2 of 17 delayed cases ($P = 1.00$). Complications were more common in the early group (66.7%) compared to the delayed group (47.1%) but were not statistically significant ($P = 0.34$). Four flaps required reexploration, with one successfully salvaged. Operative time and hospital stay were slightly longer in the delayed group but did not reach statistical significance.

Conclusion: Free flap reconstruction remains a reliable option for limb salvage in high-voltage electrical burns. A biologically timed approach—delaying reconstruction until tissue demarcation and vascular stability—may minimize complications while maintaining high flap survival rates.

Key Words: electrical burns, extremity injuries, flap timing, free flap reconstruction, microsurgery

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High-voltage electrical injuries are among the most challenging forms of trauma to manage in reconstructive surgery, particularly when the extremities are involved. These injuries often result in extensive soft tissue loss, exposure of vital structures, and unpredictable zones of tissue viability. Unlike mechanical trauma, the extent of internal damage in electrical burns can evolve over time because of subclinical tissue necrosis and progressive vascular compromise, making early surgical decisions complex.[1,2]

Microsurgical free tissue transfer offers a versatile and effective option for soft tissue reconstruction in such cases, especially when local options are unavailable or inadequate.[3,4] The principles guiding free flap reconstruction in burn care have been shaped by both timing and tissue condition. Although early flap coverage may be associated with certain advantages, its feasibility in electrical burns is influenced by multiple factors—most notably, the evolving nature of the wound and the need for serial debridement.[5,6]

This study presents our experience with microsurgical reconstruction in patients with high-voltage electrical burns of the extremities at a tertiary burn center in Central India. Emphasis is placed on patient selection, surgical timing guided by clinical judgment, flap outcomes, and complication profiles. The goal is to contribute data from a pragmatic, context-specific reconstructive approach and to support flexible, evidence-informed decision-making in the microsurgical management of electrical burn injuries.

OBJECTIVES

The primary objective of this study was to compare flap-related outcomes—including survival and complication rates—between early (<21 days) and delayed (>21 days) free flap reconstruction in high-voltage electrical burns of the extremities. Secondary objectives included evaluating the need for reexploration, duration of operative time, and hospital stay.

MATERIAL AND METHOD

This retrospective observational study was conducted at the Department of Burns and Plastic Surgery, a tertiary referral center in Central India. Over a period of 30 months from July 2022 to December 2025, we analyzed the medical records of patients who sustained high-voltage electrical injuries and underwent microsurgical free flap reconstruction for extremity defects. Institutional ethics committee clearance was obtained prior to data collection.

Patient Selection

Patients were selected based on the following criteria:

- **Inclusion criteria**:
  - Sustained a high-voltage (>1000 V) electrical contact burn
  - Involvement of the upper or lower limbs
  - Underwent free flap reconstruction for primary burn wound coverage
  - Age ≥ 15 years
- **Exclusion criteria**:
  - Low-voltage electrical burns
  - Flash burns
  - Patients reconstructed using only pedicled flaps
  - Those who underwent secondary reconstruction procedures

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- ◦ Incomplete medical records
- ◦ Children (<15 years old)

A total of 23 patients met the criteria and were included in the final analysis.

Narrative of Surgical Management

All patients were admitted through the burns emergency pathway and managed initially with standard fluid resuscitation protocols and wound care. The affected limbs were evaluated for depth of injury, neurovascular compromise, and signs of compartment syndrome. In several cases, fasciotomies were performed at admission.

The surgical team adopted a cautious and staged approach. The guiding principle was that flap timing should be dictated by wound biology. Almost all patients required at least 2 formal surgical debridements. These were performed with the goal of excising nonviable tissues while preserving critical structures wherever possible. Debridements were done under general anesthesia, and only when the wound bed demonstrated a well-perfused base free of slough and infection was flap coverage considered.

Free flap reconstruction was performed once the patient was hemodynamically stable and infection-free and the recipient zone was well-defined. Flap selection was based on the size and location of the defect, availability of donor tissue, and reconstructive goals. Commonly used free flaps included the latissimus dorsi muscle flap, gracilis muscle, and anterolateral thigh (ALT) flap. The flaps were harvested under loupe magnification, and microvascular anastomoses were performed using standard suturing technique in most of the cases, in 3 cases where vessel discrepancy was noted. Interrupted horizontal micro-mattress sutures were used.[7,8] Recipient vessels were carefully chosen outside the zone of injury to ensure reliable flow.

Notably, only 6 cases could be reconstructed within the first 3 weeks post injury—primarily due to the need for repeated debridement in the remaining patients. Thus, our cohort naturally divided into 2 timing groups: early reconstruction (<21 days) and delayed reconstruction (>21 days).

Following flap inset, patients were monitored closely in a high-dependency setting. Hourly flap monitoring was conducted for the first 48 hours, followed by 4–6 hourly checks. Clinical signs—color, temperature, capillary refill, and prick bleeding—guided early detection of vascular compromise. In cases of doubt, flap capillary blood glucose testing was used as an adjunct.[9,10]

Patient data were recorded, including demographic details, injury characteristics, timing of flap surgery, type of flap used, operative duration, outcomes, and hospital stay. Flap-related complications were classified into major (total loss, reexploration) and minor (marginal necrosis, partial graft loss, purulent discharge).

Flap survival was defined as the successful take of the flap with maintained vascularity and functional coverage. Patients were followed up to 3 months after discharge.

RESULTS

A total of 23 patients with high-voltage electrical contact burns involving the extremities underwent free flap reconstruction during the study period. The patient cohort consisted predominantly of males (male-to-female ratio of approximately 10:1), with an age range of 15 to 60 years. All patients had sustained full-thickness burns with exposed vital structures (tendons, bones, or joints), necessitating microsurgical soft tissue coverage. Most defects involved the wrist and adjacent forearm region, reflecting the predominance of upper limb injuries in our cohort. Overall, 16 patients had involvement of the hand, wrist, or forearm, whereas foot and ankle defects were seen in 7 cases. This distribution mirrors the typical hand-to-foot current pathway observed in high-voltage electrical injuries, and the ALT flap was the most commonly used flap for coverage.

Timing of Flap Coverage and Outcomes

Patients were grouped based on the timing of reconstruction:

- Early group: 6 patients underwent reconstruction within 21 days.
- Delayed group: 17 patients underwent reconstruction after 21 days, typically after at least 2 debridements.

The overall flap survival rate was 87% (20 out of 23 flaps).

Although flap failure rate was slightly more frequent in the early group, the difference was not statistically significant (Fisher's exact test, $P = 1.00$; odds ratio [OR] = 1.5, 95% confidence interval [CI]: 0.11–20.30) (Table 1).

Complications

Postoperative complications were categorized as either major (eg, flap failure, reexploration) or minor (eg, infection, graft loss).

- In the early group, 4 of 6 patients (66.7%) experienced complications:
  - ◦ 1 total flap failure
  - ◦ 1 reexploration (able to salvage)
  - ◦ 1 case of local infection (managed conservatively; Fig. 1)
  - ◦ 1 case underwent amputation of the hand distal to free flap
- In the delayed group, 8 of 17 patients (47.1%) developed complications:
  - ◦ 2 total flap failures
  - ◦ 2 partial skin graft losses
  - ◦ 1 marginal flap necrosis
  - ◦ 1 suture line dehiscence
  - ◦ 2 local infections

Although complication rates were numerically higher in the early group, this difference was not statistically significant (Fisher's exact test, $P = 0.34$; OR = 2.25, 95% CI: 0.32–15.76) (Table 2). Among the flaps that developed signs of venous congestion, 4 underwent surgical reexploration. Of these, only 1 flap was successfully salvaged, resulting in a reexploration rate of 17.4% (4/23) and an overall salvage rate of 25% (1/4). The mean operative time in the early reconstruction group was approximately 6.0 hours, with a standard deviation of ±0.6 hours. In comparison, patients in the delayed group underwent slightly longer procedures, averaging 6.5 ± 0.7 hours. Similarly, the average hospital stay was longer in the delayed group, with patients remaining admitted for 46 ± 7 days, compared to 35 ± 5 days in the early group. Despite these observed differences in both operative time and hospitalization, statistical analysis did not reveal any significant association between reconstruction timing and these parameters ($P > 0.05$). Follow up, patients showed stable coverage and soft tissue contour (Fig. 2) in all survived flaps. As this was a retrospective study without formal functional scoring, only qualitative assessment was possible. Upper limb cases demonstrated return of protective sensation and the ability to perform light daily activities after reconstruction. All lower limb patients with surviving flaps were able to ambulate independently within 3 months, with stable, durable soft-tissue coverage. To further assess whether flap type influenced reconstructive success, patients were

TABLE 1. Comparison of Flap Failure Rates in Early (<21 Days) vs Delayed (>21 Days) Reconstruction Groups

Timing Group	Flap Success	Flap Failure	Total	Success Rate
Early (<21 days)	5	1	6	83.3%
Delayed (>21 days)	15	2	17	88.2%
Total	20	3	23	87%

FIGURE 1. A, High-voltage electrical burn injury to the right wrist with postdebridement exposure of necrosed flexor tendon and median nerve. B, Post debridement, anterolateral thigh flap harvested from the left thigh. C, Secondary suturing performed because of postoperative infection.

stratified into muscle flaps and fasciocutaneous flaps, and flap survival was found to be comparable across both groups (Table 3).

DISCUSSION

In our study of 23 patients undergoing free flap reconstruction for high-voltage electrical burns of the extremities, the mean age was 34.8 years, which is comparable to findings in prior studies. Castro et al[11] reported a mean age of 25.8 years in their early microsurgical series, whereas Verdaguer et al[12] documented an average of 36.7 years in patients receiving ALT flaps. Our cohort ranged from pediatric to late-adult patients, thus offering a broader age spectrum than many previously published reports.

We also observed a clear male predominance (21 males, 2 females), consistent with studies by Shen et al,[13] Kasmirski et al,[14] and Castro et al,[11] all of which attribute this trend to the higher occupational exposure of males to high-voltage environments. Regarding injury distribution, upper limb involvement was more common (n = 16) than lower limb involvement (n = 7), echoing the patterns reported by Shen et al[13]and Jabir et al,[15] likely reflecting the typical hand-to-foot current pathway in electrical injuries.

The overall flap success rate in our series was 87.0%, with 1 failure in the early group (<21 days) and 2 in the delayed group (>21 days). Although this suggests a slightly better survival in delayed reconstructions (88.2%) compared to early ones (83.3%), the difference was not statistically significant (P = 1.00; OR = 1.5, 95% CI: 0.11–20.30). These results are consistent with success rates reported by Shen et al[13] (87%) and Monga and Goil[16] (85.3%). However, unlike Monga and Goil,[16] we do not recommend single-stage composite reconstruction in electrical burns. A failed flap in this setting carries the risk of losing vital tendon or nerve transfers along with soft tissue cover, which, given the limited availability of donor tissue in electrical burns, is a costly setback. Our study supports a staged reconstruction strategy; this approach is both safer and more sustainable in high-voltage electrical injuries, which often have unpredictable zones of necrosis and compromised vascularity.

The issue of timing remains central to flap outcomes. Alessandri-Bonetti et al[17] (2024), in a systematic review of 275 flaps, demonstrated that the intermediate timing window (5–21 days) is associated with the highest flap failure rate (16.6%), whereas ultra-early (0–4 days, 7.3%) and delayed (>21 days, 6.7%) reconstructions yielded better outcomes. Our findings fit within this framework: the single early failure occurred within 21 days, whereas the 2 delayed failures arose in cases with residual vascular compromise despite biologic delay. This underscores that biologic readiness—not rigid time intervals—should guide the timing of reconstruction. Kasmirski et al also found an overall failure rate of 9.9%, in 475 flaps with return to operation theater in 20.6%. In our cohort, 4 flaps required reexploration due to venous congestion (17.4%), and only 1 was salvaged; this highlights the difficulty of reversing vascular thrombosis in electrical burns, even with timely intervention. Importantly, no postoperative vascular blowout was encountered in this series, even in cases requiring reexploration.

Similar observations were reported by Thomson et al,[18] who analyzed 7 cases of high-voltage electrical burns treated with a single aggressive debridement followed by delayed free flap coverage. Despite performing reconstruction beyond the traditional early window, they achieved a flap survival rate of 85.7%. The authors concluded that timing beyond 3 days did not compromise outcomes, provided the wound was adequately debrided and recipient vessels were appropriately selected.

In a series of 17 high-voltage electrical burns coverage by free flaps, Sauerbier et al[19] found that all 5 flap failures occurred between days 5 and 42 post injury, and notably, no failures occurred during secondary reconstruction. They used a range of flap types and demonstrated that early muscle flaps were most commonly applied in electrical injuries, whereas cutaneous and fascial flaps were preferred later in the treatment course. Our findings show a similar trend, but in our cohort, flap survival did not show any meaningful difference between muscle-based flaps and fasciocutaneous flaps, supporting that flap type alone is not a determining factor of outcome in electrical burns.

Our findings are also supported by the prospective study by Mene et al,[6] who examined forearm electrical burns and emphasized the importance of delayed vascularized coverage following early

TABLE 2. Complication Rate by Timing of Reconstruction

Timing Group	With Complications	Without Complications	Total
Early (n = 6)	4	2	6
Delayed (n = 17)	8	9	17

FIGURE 2. A, Burn injury involving the posterior aspect of the lower third of the leg and heel. B, Intraoperative view of the harvested free gracilis muscle flap. C, Three-month postoperative follow-up showing stable coverage and contour.

debridement. In their initial attempts, early free flaps failed because of progressive necrosis and vessel instability. The study concluded that waiting until the wound stabilized and vascular integrity was confirmed led to better flap survival and overall outcomes.

Burn-induced coagulation disorders are another factor influencing flap outcomes. Sherren et al[20] and Guilabert et al[21] have described a biphasic coagulopathy: early hypocoagulability followed by a prothrombotic state that may persist for weeks. Such systemic changes can impair flap microcirculation, particularly during the intermediate postburn phase. Interestingly, despite this, we noted fewer flap failures in our delayed group, reinforcing that delaying reconstruction until systemic and local inflammation subsides is not only safe but also advisable.

Flap selection also plays a crucial role. Verdaguer et al[12] successfully used ALT flaps exclusively in their acute burn series. However, in our cohort, we adopted a versatile flap selection strategy, using various type of flaps based on the defect location, available donor sites, and intraoperative findings. This approach is consistent with that of Jabir et al[15] who advocate for individualized planning in burn reconstruction due to the heterogeneity of injury zones. In our series, recipient vessels were selected outside the zone of electrical injury to ensure reliable perfusion. For upper-limb defects involving the hand, the radial artery and its accompanying venae comitantes were used for microvascular anastomosis. In wrist and forearm defects, healthy arterial segments proximal to the zone of injury were chosen. For lower-limb reconstruction, the anterior tibial or posterior tibial vessels were selected depending on the defect location and extent of injury.

Complication rates were slightly on the higher side in early groups. Although flap survival is critical, our findings emphasize that early reconstruction may not prevent progression of deep tissue damage, as seen in a hand case where amputation was eventually required despite flap viability. In this case, a flow-through ALT flap was used to augment distal perfusion, and although the flap remained fully viable, progressive distal vascular insufficiency led to loss of the hand—highlighting the inherent limitations of flow-augmentation strategies when underlying electrical injury continues to evolve (Fig. 3). Minor issues such as partial graft loss, marginal necrosis, suture dehiscence, and localized infections occurred but were managed conservatively.

A 2018 meta-analysis[22] on lower limb trauma reconstruction favored performing free flaps within 72 hours for mechanical injuries; however, this strategy does not translate well to electrical burns, where tissue viability evolves unpredictably for days to weeks. In our study, higher complication rates in early reconstructions support favoring a biologically timed approach. Pan et al[23] also reported excellent flap survival in acute hand burns regardless of timing but acknowledged that electrical burns behave differently from thermal or mechanical injuries. This distinction underscores the need to avoid direct extrapolation from trauma protocols to electrical burns.

Our findings, supported by current literature, highlight that in high-voltage electrical burns, reconstruction timing should be guided by tissue biology rather than rigid timelines. Delaying free flap coverage until wound demarcation and vascular stability are achieved helps reduce flap loss and complications. This approach emphasizes the value

TABLE 3. Flap Survival and Complications in Muscle Versus Fasciocutaneous Free Flaps Following High-Voltage Electrical Burns

Flap Type	No. Flaps (n)	Survived (n)	Failed (n)	Failure Rate
Muscle flaps	7	6	1	14.3%
Fasciocutaneous flaps	16	14	2	12.5%
Total	23	20	3	13%

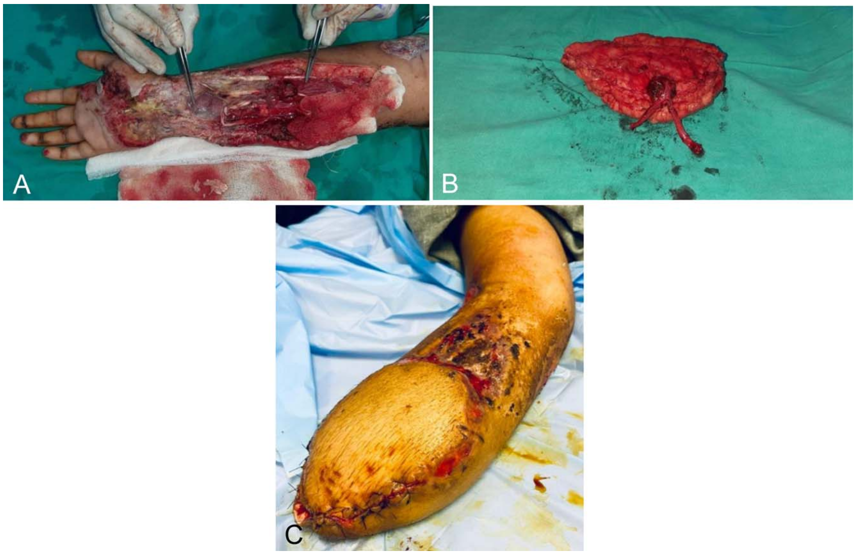

FIGURE 3. A, High-voltage electrical burn involving the right hand, wrist, and forearm, followed by progressive hand congestion noted 1 week post injury. B, Anterolateral thigh flap harvested and used as a flow-through flap to improve distal hand perfusion. C, On postoperative day 10, despite flap survival, distal hand perfusion failed, necessitating amputation.

of a biologically timed strategy for safe and reliable soft tissue reconstruction in electrical burn injuries.

Limitation of the Study

This retrospective, single-center study is limited by a small sample size and potential selection bias. Flap heterogeneity and lack of randomization may limit intergroup comparisons. Long-term functional outcomes and scar quality were not assessed, and follow-up was limited to short-term to midterm observation.

CONCLUSION

Free flap reconstruction for high-voltage electrical burns of the extremities showed a good overall success rate with acceptable complication rates, most of which were managed conservatively. Timing of reconstruction, whether early or delayed, did not show a statistically significant impact on flap failure or complication rates. However, cases managed after wound demarcation and at least 2 debridements tended to exhibit fewer major complications, highlighting the importance of biologic readiness rather than strict timing.

Flap success in our series was independent of flap type, with both muscle and fasciocutaneous flaps providing reliable coverage when anastomosed outside the zone of injury. Notably, early coverage did not prevent progression of deep tissue damage in electrically injured hands, reinforcing that wound biology plays a decisive role in ultimate limb salvage.

Overall, our findings support a flexible, case-specific, biologically guided reconstructive strategy to optimize microsurgical outcomes in high-voltage electrical burn extremity injuries.

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