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ORIGINAL ARTICLE

Outcomes following replantation surgery

Krystle R. Tuaño[1] · Justin C. McCarty[1] · Marlie H. Fisher[2] · Kyle R. Eberlin[1]

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Abstract
The ability to perform surgical replantation of individual digits and limbs can provide substantial functional improvement for patients who sustain devastating upper extremity injuries. Defining success in replantation surgery extends beyond the acute period and the binary metrics of survival or loss of the replanted part to include the long-term overall functional outcomes. Functional outcomes include both objective clinical evaluation and patient-reported outcomes. There has been significant variation in the way outcomes following replantation are measured, which inherently leads to heterogeneity in the reported outcome data. Given the variability among outcome measures, we aim to explore the outcomes of replantation surgery, particularly clinical evaluation and patient-reported functional outcomes following replantation.

Keywords Digit replantation · Outcomes after replantation · Functional outcomes · Patient-reported outcomes · Outcome measures · Digit replantation survival · Digit replantation function

Introduction

Worldwide, upper extremity amputations continue to occur frequently, with age standardized incidence rates of 24 per 100,000 for thumb amputations and 56 per 100,000 non-thumb amputations as of 2017 (Table 1) [1]. While high-income countries continue to account for the majority of amputations, there has been a disproportionate trend of increasing rates of amputations in patients residing in low- and middle-income countries. Treatment options following amputation include replantation or completion/revision amputation. Although common in many European countries, there are efforts to identify and select regional Hand Trauma centers in the USA with expertise in managing these challenging injuries [2, 3].

Indications for replantation surgery have fluctuated over time as research has attempted to delineate which patients derive benefit from replantation compared to undergoing revision/completion amputation as graded by both replant survival and functional and patient-reported outcomes [4]. Contemporary indications for replantation surgery include hand, forearm, and more proximal amputations, any thumb amputation, multiple digital amputations in an adult, or any amputation in a child [5–7]. Patient selection is paramount as patients with peripheral vascular disease, history of smoking, or other significant medical comorbidities may be poor candidates for replantation as they have both lower replant survival and poorer outcomes[4, 8].

Ultimately, the assessment of the appropriateness for replantation is based on the examination of the amputated part and residual limb in the operating room [9]. Injury mechanisms most favorable for replantation are guillotine (clean and sharp amputation) or other mechanisms of amputation with minimal local tissue damage [9]. Crush and avulsion injuries are less likely to be salvageable if there is severe vascular injury, demonstrated by “red line sign,” which are small hematomas in the skin along the neurovascular bundle, or “ribbon sign,” which is a corkscrew appearance of the arteries [10]. The initial tendency to replant all amputated parts has evolved toward the goal of maximizing functionality for each individual patient, as replantation without function or sensation is not an acceptable outcome for patients.

Krystle R. Tuaño and Justin C. McCarty: Co-first authors.

✉ Kyle R. Eberlin
keberlin@mgh.harvard.edu

[1] Division of Plastic and Reconstructive Surgery, Massachusetts General Hospital, 55 Fruit Street, Boston, MA 02114, USA

[2] Division of Plastic and Reconstructive Surgery, University of Colorado Hospital, Denver, CO 80045, USA

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Table 1 Age standardized global incidence of digit amputation [1]

	Age-standardized incidence rate (ASIR) in 2017 per 100 000, estimate (95% UI)	
	Thumb amputation	Non-thumb amputation
Overall	24.1 (17.4 to 33.9)	56.0 (43.4 to 74.0)
Sex		
Male	31.4 (22.9 to 43.2)	77.3 (60.6 to 100.2)
Female	16.8 (11.5 to 25.2)	34.5 (25.5 to 48.3)
Socio-demographic index		
Low	18.6 (13.4 to 25.6)	55.3 (42.7 to 73.1)
Middle	18.5 (13.5 to 25.4)	36.8 (28.4 to 48.3)
High	44.0 (30.2 to 64.7)	85.1 (63.0 to 114.5)

Adapted from Crowe, C. S. et al. Global trends of hand and wrist trauma: a systematic analysis of fracture and digit amputation using the Global Burden of Disease 2017 Study. *Inj Prev* **26**, i115-i124 (2020)

UI: uncertainty interval

Replantation survival

The first objective of replantation surgery is vascular survival of the replanted part. In the postoperative period, monitoring perfusion and vascular patency is key to the survival of the replant [11]. Clinical signs include color, turgor, capillary refill, bleeding on pinprick, and temperature of the replanted digit or limb. A successful replant will typically exhibit a pink or red color, feel warm to the touch, and have a capillary refill time of two to three seconds. Signs of arterial compromise include delayed capillary refill and reduced turgor of the tissue; venous occlusion may result in the part appearing edematous and blue with a rapid capillary refill.

In general, survival rates following replantation surgery in the literature range from 60–90% for various levels of amputations [4]. Survival rates depend on multiple factors, including the level of amputation, the mechanism of injury, ischemia time, the presence of comorbidities, and the technical expertise of the surgeon [12, 13]. A meta-analysis in 2006 found the rate of survival of digits based on injury mechanism was 91% for clean cut amputations, 68% for crush injuries, and 66% for avulsions [4]. The zone of injury rate of survival was lowest for replantation at the level of the distal phalanx at 77% but in general for all digit and thumb replants ranged from 77 to 89%. Ischemia time effects more proximal upper extremity amputations to a greater degree than digital and thumb amputations where the recommended times are 8 h of warm ischemia or 30 h of cold ischemia. More recent data has shown that there is no significant difference between delayed compared to immediate digital replantation with survival rates of 88% for delayed and 84% for immediate replant [14]. This is relevant for surgeon decision making as it potentially enables the option of delaying replantation until normal working hours when there are optimal conditions including experienced staff and full teams.

Patient comorbidities also influence the success of upper extremity replantation surgery. Medical conditions including psychotic disorders, diabetes, peripheral vascular disease, collagen vascular diseases, and autoimmune disorders increase the risk of replant loss and subsequent complications during and after surgery, such as infection, poor wound healing, and impaired perfusion [4, 15–17]. Psychotic disorders had a highest relative risk of replant failure at 1.79 followed by peripheral vascular disease with a 1.41 relative risk of failure [17]. Cumulative number of pre-procedural comorbidities is associated with increased risk of replantation failure as well. Additionally, smoking and obesity negatively impact the success of replantation surgery by increasing the risk of complications and impairing wound healing [15, 18].

Surgeon skill and hospital ancillary staff experience with replantation surgery, which is often evaluated using hospital volume or years in practice as a surrogate, is known to effect outcomes. Hospital annual volume increases the odds of replant success with those hospitals performing over 5 replantations yearly having a 75% success rate compared to 64% for those which perform fewer [19]. Increasing experience with replantation further also increases the likelihood the replant will be attempted as compared to revision amputation. Increasing experience of the surgeon and staff translates to the postoperative period when monitoring the replanted part as they speed recognition of vascular issues and intervention. Several measures may increase the vascular success of the replant, including taking down constrictive dressings or sutures, leeches or heparin soaked gauze to encourage blood egress if there is venous congestion, or return to the operating room for exploration or revision of the vascular anastomosis [20, 21].

There are many studies reporting on the success of replantation surgery regarding viability. Fufa et al. defined survival of replanted digits at the 21 day mark, finding an overall survival rate of 57% [22]. Systematic reviews have been performed of replantation studies in the literature, demonstrating survival rates in the 60–90% range even in the setting of avulsion injury mechanisms [4, 23, 24]. In a recent study, Cho et al. reported on 14,872 patients who sustained a single digit amputation between 2001–2014, and only 11% of these injuries underwent replantation although more than 80% were reported to be successful [25].

In the future, prospective studies with similar outcome metrics will be required to provide comparison for vascular survival of replantation. We agree with the assertion by Cho, Kotsis, and Chung that the survival of replanted digits be measured at least 21 days following replantation to ensure definitive viability of the replanted part [26].

Functional outcomes following replantation

Survival of the replanted part is necessary to portend functional recovery; it is, however, not the definitive measure of functional success. Following replantation, patients may experience reduced range of motion or difficulty with fine motor tasks, even if the replanted digit has regained a modicum of function. Traditional outcome measures are reported inconsistently and vary widely in the literature [27, 28]. The timing of functional assessment plays a large role in determining the success of the procedure, as immediate versus late functional outcomes depend greatly on the mechanism of injury [13]. Objective measures of function help clinicians identify areas where the patient is experiencing functional limitations and guide postoperative rehabilitation efforts. The surgeon has myriad ways to determine functional recovery following replantation, including total active range of motion, sensation, and grip strength, among others. The highest level of data to date with comprehensive assessment of outcomes comparing replantation compared to revision amputation comes from the FRANCHISE multicenter international retrospective cohort study and is presented below within each category of outcome (Table 2) [29].

Total active range of motion (TAM) measured using a goniometer is the sum of active range of motion at the metacarpophalangeal, proximal interphalangeal (PIP), and distal interphalangeal joints for each digit [26]. TAM enables the clinician to understand how the patient's hand functions by accounting for any joints that are fused, range of motion of remaining joints, and the flexor and extensor functions [26]. TAM values following amputation vary based on the level of the amputation. Distal amputations in zone I maintain PIP joint and FDS insertion, and thus are expected to maintain greater range of motion (ROM) postoperatively. Buntic et al. demonstrated a TAM of 170° for zone 1 injuries and 133° for zone 2 injuries across 23 replant/revascularization cases, with high levels of patient satisfaction [30]. In the FRANCHISE study for single finger amputation distal to the PIP joint, PIP joint ROM was significantly better for replant at 83° versus 71° for revision amputation [29]. Amputations proximal to the PIP joint, however, demonstrated no significant differences in ROM favoring either revision amputation or replantation.

Sensation measured using 2-point discrimination (2PD) and Semmes–Weinstein (SW) monofilament testing is key metric as replanted digits without adequate sensation are at risk of injury during normal activities of daily living or are not used by the patient via compensation mechanisms. Sensory outcome data following replantation are mixed; Boeckx et al. reported only 3% of patients had 2PD less than 6 mm, 34% had 6-15 mm 2PD, and 34% had greater than 15 mm 2PD [31]. In a large meta-analysis of 367 fingers and 87 thumbs with a mean follow-up of 33.5 months, Glickman and Mackinnon reported a mean 2PD of 11 mm in the thumb and 12 mm in finger replantations [32]. In the FRANCHISE study, the mean 2PD was 8.44 for those undergoing replantation and was not significantly different than those undergoing revision amputation [29]. Within assessed subgroups, 2PD was superior in revision amputation in single finger amputations distal to the PIP with an adjusted mean difference of 1.45 mm and for thumb only amputation proximal to the IP joint (adjusted mean difference 3.76). No significant differences were seen in SW monofilament testing with mean values of 9.77 for replantation versus 13.50 for revision amputation.

Grip strength measured using a dynamometer is reliable and common method to evaluate grip strength [26]. Sebastian and Chung recommend reporting ratios comparing the

Table 2 Multivariable outcomes after revision amputation compared to replantation (adapted from the FRANCHISE study)[29]

	Mean (SD)			
	Revision amputation	Replantation	Adjusted mean difference (95% CI)	*p*-Value
MHQ	76.81 (18.93)	76.78 (17.64)	5.93 (1.03 to 10.82)	*0.02
DASH	13.84 (16.12)	11.29 (14.86)	−4.29 (−8.45 to −0.12)	*0.04
PROMIS	70.63 (12.32)	73.50 (9.37)	3.44 (0.60 to 6.28)	*0.02
2PD	6.80 (3.30)	8.44 (4.26)	0.76 (−0.31 to 1.83)	0.17
SW monofilament	13.50 (42.56)	9.77 (36.51)	2.17 (−8.73 to 13.06)	0.70
Grip Strength	31.54 (13.79)	32.36 (14.18)	2.34 (−1.37 to 6.05)	0.22
Finger MCP joint ROM	76.28 (13.35)	75.77 (16.18)	2.29 (−3.10 to 7.68)	0.41
Finger PIP joint ROM	70.14 (30.51)	74.93 (38.79)	4.21 (−11.87 to 20.30)	0.61

Adapted from Chung, K. C. et al. Patient-Reported and Functional Outcomes After Revision Amputation and Replantation of Digit Amputations: The FRANCHISE Multicenter International Retrospective Cohort Study. *JAMA Surg* **154**, 637–646 (2019)

*Denotes significant values at $p < 0.05$

injured to the uninjured side rather than population normative values [13]. Chen et al. found that the average grip strength following single digit replantation was 39.6 kg, 91% of the uninjured hand, and that this was the most important factor related to a positive outcome [33]. In the FRANCHISE study, grip strength was 32.36 kg after replantation which was not significantly different than after revision amputation [29]. This is consistent with recent publications by Bott et al. who concluded that grip strength was not significantly different between replantation and revision amputation and that digits after replantation could achieve 78.7% of the patients uninjured hand compared to 87.9% for the revision/completion amputation cohort [34]. Furthermore, in contrast to the FRANCHISE study, the authors found notable differences in grip strength favoring thumb replantation of 91.5% compared to 66.0% for those undergoing revision/completion amputation.

Patient-reported outcomes following replantation

Patient-reported outcomes (PROs) are a crucial measure of the success of replantation surgery as the healthcare system moves toward a patient-centered long term outcome focus. Patients reported outcome measures (PROMs) encompass a wide range of survey style questions to better understand their functional abilities, quality of life, and overall satisfaction with a given procedure or disease. PROMs, depending on the instrument used, assess a range of factors, including pain levels, sensation, mobility, and strength. Patients may also be asked to provide feedback on their ability to perform specific tasks, such as typing or writing, and to rate their overall satisfaction with their functional abilities and quality of life following surgery. PROMs are an essential tool for understanding the effectiveness of replantation surgery in improving patients' lives and for identifying areas where further improvements can be made in surgical techniques and postoperative care.

Multiple PROMs are used in hand surgery which provide varying insight into understanding the patient experience and outcomes. The Michigan Hand Outcomes Questionnaire (MHQ), the Disability of Arm, Shoulder, and Hand (DASH) questionnaire, the Patient-Reported Outcomes Measurement Information system (PROMIS), and 36-item Short-form health survey are validated instruments which provide valuable information on the patient's perception of their functional abilities and quality of life following trauma [35]. Yoon et al. evaluated these instruments in hand surgery specifically for evaluating amputation and found the MHQ and DASH correlate strongly with each other while the PROMIS score had fair correlation with its primary use being to add adjunctive information [36]. The 36-Item Short-Form Health Survey had poor correlation and likely should not be used as a primary assessment tool but can provide information on overall quality of life. These PROMs assess a range of factors, including pain levels, sensation, mobility, and strength.

The Michigan Hand Questionnaire (MHQ) assesses several domains of hand function including activities of daily living, work-related activities, pain, overall hand function, and patient satisfaction [37]. The questionnaire consists of 37 items, with each item scored on a scale of 0 to 100, with 100 indicating optimal function. The domains are then weighted and combined to produce a summary score, ranging from 0 to 100, with higher scores indicating better function. The MHQ is a reliable and valid tool for assessing hand function after replant surgery, and it has been used in numerous studies to evaluate the effectiveness of replantation and other functional hand procedures [37–40]. The MHQ is often used in combination with other objective assessment tools, such as grip strength, range of motion, and sensation to provide a comprehensive evaluation of hand function after replantation.

The Disabilities of the Arm, Shoulder and Hand (DASH) questionnaire is designed to assess the impact of upper extremity dysfunction on a patient's ability to perform daily activities [41]. The questionnaire consists of 30 items, with each item scored on a scale of 0 to 5, with 5 indicating the greatest disability. The items are then combined and converted to a score ranging from 0 to 100, with higher scores indicating greater disability [26]. Like the MHQ, the DASH questionnaire is a reliable and valid tool for assessing upper extremity function in patients with a variety of upper extremity conditions, including replant surgery [13].

Several measures exist for capturing the spectrum of replant recovery using both PROs and objective measures. Tamai's criteria assess functional outcomes based on seven categories, including pain, cold intolerance, range of motion, grip strength, sensitivity, appearance, and the ability to perform activities of daily living [42]. Chen's criteria also assess functional outcomes based on seven categories, including appearance, range of motion, grip strength, sensation, pain, cold intolerance, and activities of daily living [43]. While both systems assess similar categories of function, Tamai's criteria include an assessment of sensitivity while Chen's criteria include a more detailed assessment of appearance. Both Tamai's and Chen's criteria are useful tools for scoring functional outcomes after digit replantation, and the choice of which system to use may depend on the individual clinician's preference and experience.

Within the FRANCHISE study, comparison of PROs between patients undergoing revision amputation compared to replant found significantly better adjusted outcomes favoring the replantation cohort for MHQ (+5.93), DASH (−4.29) and for PROMIS scores (+3.44 adjusted mean difference). Patients who had amputation of 3 or more digits and underwent replantation compared to revision amputation garnered the most significant benefit with absolute mean differences for the MHQ (+23), DASH (−31) and PROMIS (+31). A systematic review and meta-analysis of outcomes following single digit replantation proximal to the FDS, in zone II, found that the MHQ was better in replantation (84.7) compared to revision amputation (76.8) despite having worse range of motion. The authors make note that over time, the ROM has improved with refinement in surgical technique.

For more proximal upper extremity amputations of the forearm, PROs also favor replantation compared to revision/completion amputation. Pet et al. Examined patients undergoing replantation vs. prosthetic rehabilitation and found better MHQ scores for the replant group compared to the prosthetic group (47 versus 35) and lower DASH scores (24.6 versus 39.8) [44]. Within specific domains, replantation resulted in better overall function and patient satisfaction.

An additional PRO that is important to understand following traumatic amputation is pain specifically as it relates to replantation surgery compared to revision/completion amputation. Vlot et al. examined 1083 patients who underwent revision or completion amputation and found that 71 (6.6%) developed a symptomatic neuroma requiring reoperation [45]. Replantation surgery provides a distal target for the transected nerve end which theoretically decreases the incidence of neuroma formation; though there is little data on the exact incidence of neuroma formation following replantation. As a surrogate for neuroma formation, Hahn et al. found 14 (2.9%) patients out of 468 digital replantations had intractable pain.

A combination of patient-reported outcomes questionnaires, functional tests, and objective measurements of strength and range of motion can provide a detailed picture of the patient's functional abilities and guide postoperative rehabilitation efforts to optimize outcomes. It is difficult to exactly quantify success of surgery, as this is multifactorial and determined with both subjective and objective measures. However, in evaluating clinical assessment with PROs, the MHQ and DASH can be used, as they correlate strongly with each other, and the PROMIS can be used to add adjunctive information. The 36-Item Short-Form Health Survey can be used to provide information on overall quality of life. These can be used in combination with Tamai's and Chen's criteria to provide a comprehensive evaluation of hand function after replantation.

Conclusion

Extremity replantation is a remarkable feat of modern medicine and has the potential to significantly improve the quality of life of patients. Assessing outcomes of replantation can be challenging given the heterogeneous nature of many prior studies, and it is essential to consider both vascular survival as well as clinical assessment with patient reported outcomes when assessing the success of surgery. The ultimate goal of replantation surgery is to restore the function of the replanted limb and improve the patient's quality of life. Future investigation is needed to develop effective and reliable tools for assessing functional outcomes and to identify strategies for optimizing functional outcomes following replantation surgery.

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Declarations

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