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Literature review

Finger and thumb replantation: From biomechanics to practical surgical applications☆

Replantations digitales : de la biomécanique à la pratique chirurgicale

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ABSTRACT

Finger and thumb amputations, which are always dramatic injuries with major functional and psychological repercussions, remain a surgical challenge. This review on digit replantation develops the underlying biomechanical and surgical aspects as well as practical indications. The different stages from trauma to postoperative monitoring are described. We describe the steps to follow from theory to practice in order to optimize the surgical acts that must as effective possible in terms of management and decision-making efficiency. Indications recognized as standards such as thumb amputation, multi-digit amputations and distal amputations are detailed, as well as the more controversial ring finger replantations. The challenge of successful finger and thumb replantation lies in searching for the best functional and cosmetic outcome and not performing irrelevant microsurgical manipulations.

RÉSUMÉ

Les amputations digitales, qui sont des accidents toujours dramatiques et aux répercussions fonctionnelles et psychologiques majeures, restent un challenge chirurgical. Dans cet article dédié aux replantations digitales, sont développés les aspects biomécaniques et opératoires sous-jacents, ainsi que des conduites pratiques. Nous décrivons les différentes étapes du traumatisme à la surveillance postopératoire. Nous proposons des conduites à tenir partant de la théorie à la pratique dans le but d'optimiser le geste opératoire qui se doit d'être le plus efficace en termes de gestion du temps et d'efficacité décisionnelle. Les indications reconnues comme des standards telles que l'amputation du pouce, les amputations pluridigitales et les amputations distales sont détaillées, ainsi que les réimplantations plus controversées comme les doigts de bague. Nous voyons que le challenge pour réussir une replantation digitale doit être celui de la recherche du meilleur résultat fonctionnel et cosmétique et non de l'exploit microchirurgical non pertinent.

1. Introduction

The first recorded upper limb replantations were performed by Malt and McKhann [1] and by Chen et al. [2], the former with an upper limb and the latter with a hand, although there is controversy as to whom performed the first [3]. Shortly after, the first successful digit replantation was carried out by Komatsu and Tamai [4] and since then, improvements in microsurgical techniques have expanded the replantation indications.

The 1970s saw the development of hand trauma centers, which combined training and practice of microsurgery, reconstructive surgery and orthopedics within a single unit [5]. This led to the concept of a one-time treatment [6].

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As finger and thumb amputations greatly affect the hand's function, it is important to promote effective and reproducible techniques, and guarantee that qualified surgeons attain a high level of expertise in this demanding procedure.

In France, university degree programs in microsurgery are diverse [7]. The latest FESUM (Federation Européenne des services Urgences Mains) publication showed that despite a 32% increase in the number of hand injuries over the last 20 years, replantations represent only 7% of the microsurgical procedures and its share has decreased [8]. The same trend has been observed in the USA, where the incidence of replantation surgery has decreased by over 50% between 2000 and 2010, with most hand surgeons performing fewer than five per year [9].

The aim of surgical replantation is vascular success and full hand function. Although often rewarding for the surgeon, success must not be equated with tissue survival; the end-goal of a reimplantation is its usefulness from a functional point of view. This explains why indications have refocused and a new consensus for reimplantation of the thumb, distal and multi-digit amputations has been reached, with broader indications in children for instance. Detailed information on the management of finger and thumb amputations may be found in teaching and instructional articles [10–12].

In this review, the general principles of digit replantation are described. The accepted indications are described in detailed. We offer microsurgical tips and discuss controversial indications, such as avulsion amputations, deducing from theory the key elements needed to optimize surgical time and achieve the best possible cosmetic and functional results after replantation.

2. Fluid biomechanics considerations

For a replanted finger to be useful to the patient, the first requirement is restoring blood circulation and ensuring vascular survival. Thus the "plumbing" is the starting point for finger or thumb restoration. In order to understand the vascular and fluid mechanics reasons for replantation failure, we will first review some classical biomechanics rules on flow patterns.

Poiseuille's experiments provided us with better understanding of body flows, whenever they are quasi-steady and taking place in channels that are minimally tortuous and not bifurcated (e.g. small blood vessels, air flow) [13]. They provided a strong argument for the no slip-condition of fluid on the wall of a pipe which determines the so-called friction factor. This strong dependence of flow rate on channel size allows the body to finely tune blood distribution through vasodilation and vasoconstriction. The corresponding laminar velocity profile is parabolic (Fig. 1A), with the velocity being zero at the channel wall (no slip boundary condition) and being at its highest in the center of the channel.

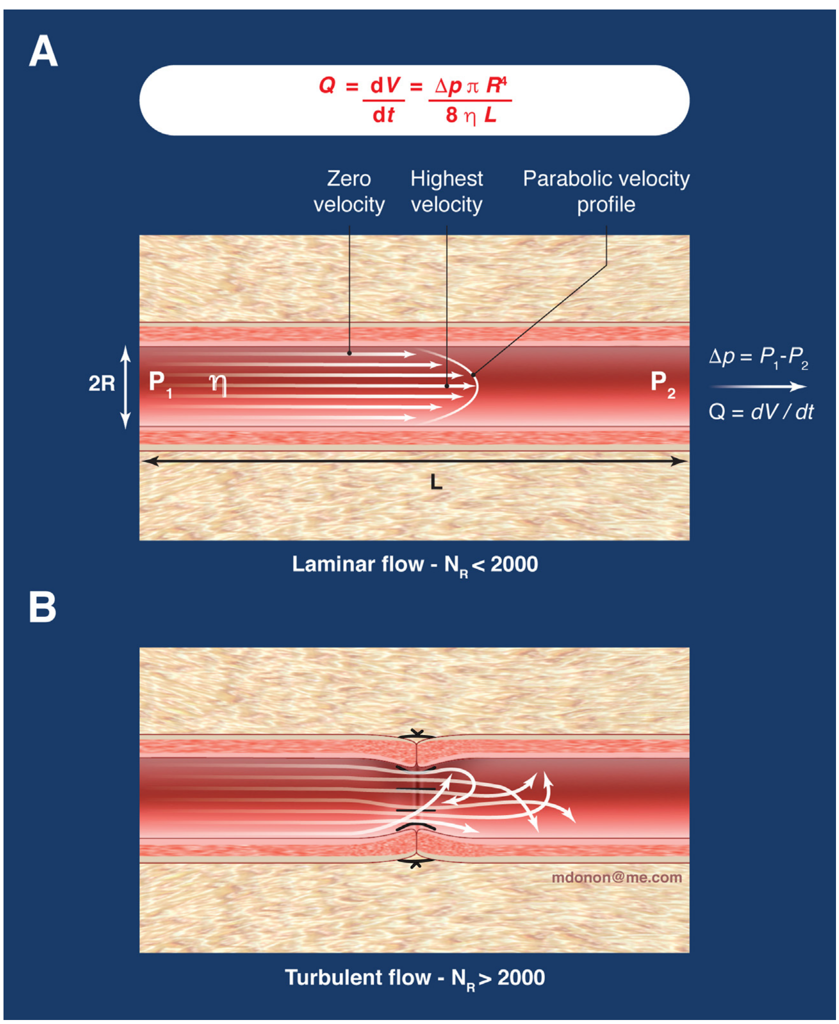


Fig. 1. Laminar flow in Poiseuille's law. Poiseuille's law describes the laminar flow of an incompressible fluid through a long tube having a constant cross section. It summarizes the relationship between flow rate and pressure drop (A). Turbulent flow conditions (B). ρ: density; η: viscosity; Q: flow rate; Δp: pressure difference; L: length of the tube; R: channel radius; N_R: Reynolds number.

Although the Poiseuille law does not strictly apply to large arteries, in which the blood flow is strongly pulsatile, it still provides an estimate of a vessel's hydraulic resistance. Such an estimate is essential to deducing the local blood flow Q in a given vessel, since in vivo blood flow is pressure-driven (and not flow rate driven). It flows from high to low pressure.

Poiseuille also described the existence of a layer of plasma devoid of red blood cells along the vessel wall, which he observed in small blood vessels. The cell-free marginal layer is the consequence of the finite size of red blood cells and of the lift force that they experience due to their deformability. This force contributes to the cells migrating towards the center of the channel. This effect is now referred to as Zweifach-Fung effect [14,15].

In large arteries, Poiseuille's equation does not apply since blood flow is pulsatile. The flow profiles in arteries were first derived by Womersley [16], who showed that they changed over time depending on the Womersley number:

$$\alpha = R\sqrt{\frac{\rho\omega}{\eta}}$$

with ω is the blood flow pulsation ($\omega = 2\pi f$, with f the frequency). The Womersley number is a dimensionless number that compares the pulsatile inertial forces to the viscous forces in the blood flow. Since blood progresses along the vasculature from a large vessel to many small vessels, the tube radius consistently decreases, while the frequency, density and dynamic viscosity (usually) remain constant throughout the network. The Womersley number is large in the aorta (α = 16 to 18), decreases along with the vessel diameter at each branching vessel and reaches very small values in the terminal capillaries ($<< 1$). The time pattern of the velocity profile has been shown within the abdominal aorta [17].

When the Womersley number is below 2.5, the pulsation frequency is sufficiently low that a parabolic velocity profile has time to develop at each instant of the cardiac cycle. The quasi-steady flow is nearly in phase with the pressure gradient and can be closely approximated by Poiseuille's law using the instantaneous pressure gradient.

In arterioles, capillaries and venules, the Womersley numbers are much less than 1. In these regions, the inertial forces become negligible and the flow is determined by the balance between viscous and pressure forces. Stokes flow conditions thus dominate within the microcirculation.

Under physiological conditions, no transition to turbulence normally occurs within the blood vessel. Turbulent flow conditions can, however, occur in certain conditions, such as stenosis, sharp turns, and protrusions within the lumen (e.g. microvascular anastomosis sutures) (Fig. 1B). In the case of a long cylindrical pipe having a constant cross section, the transition from laminar to turbulent flow is governed by the Reynolds number

$$N_R = \frac{\rho(2R)V}{\eta},$$

where $2R$ is the vessel diameter and V is a characteristic velocity, typically the mean velocity $V = Q/\pi R^2$. This transition is influenced by pulsatility [18]. There is no impact at the high frequency limit ($\alpha \gtrsim 12$), as flow variations are too fast to impact turbulence (critical Reynold number $N_{Rc} \sim 1800$). The same conclusion holds in the low Womersley regime ($\alpha \lesssim 2.5$), where the flow structures adjust to the instantaneous Reynolds number ($N_{Rc} \sim 3000$). In the intermediate range of Womersley number ($2.5 \lesssim \alpha \lesssim 12$), the critical Reynolds number transitions smoothly between the two N_{Rc} limits.

3. Efficient workflows and procedures in the replantation environment

3.1. Prior to patient arriving in emergency department

Prior to the patient arriving in the emergency department (ED), certain rules must be followed to optimize the success rate:

- transport of amputated parts on ice packs without direct contact;
- no colored antiseptic solution as it can damage and color tissues;
- special shipping boxes for amputated parts with time of injury and patient details;
- exact time of injury noted on the emergency report in order to calculate the ischemia time of the amputated part;
- no need to apply a tourniquet: compressive dressing is sufficient.

The classic teaching rule is a maximum ischemia time of 6 hours before replantation as ischemia time influences the success rate and functional results, mostly in above-hand proximal replantation. In thumb/finger and distal amputations, longer ischemia times do not negatively impact the success of digit replantation. Recent literature shows no significant statistical difference in survival rates with more or less than 12 hours of ischemia. Nonetheless, the main point is not that extended ischemia is well tolerated in finger replantation, but rather that delaying the replantation overnight can be considered [19–21].

3.2. When patient arrives in emergency department

Upon the patient's arrival in the ED, the operating room (OR) staff and anesthesia teams should be notified. It is essential to rule out any potentially life-threatening lesions or conditions that can delay replantation. X-rays of the patient's hand and of the amputated part(s) are obtained as well as preoperative laboratory blood tests. A tetanus vaccination is given if indicated.

As soon as possible, the amputated part is delivered to the OR or both the patient and amputated part are sent together; however this must only occur after the administrative registration process is completed to avoid patient error.

3.3. First steps in operating room

The OR staff should prepare a side table with ice packs, a second set of microsurgical instruments, heparinized saline, micro- and small vascular clip appliers, hand surgical instruments and 9-0 and 10-0 nylon sutures. Both the mini C-arm and surgical microscope should be prepared, the former to confirm the type of bone fixation in the amputated part and the latter for side table dissection. The surgeon then takes the amputated part to the OR to prepare it for replantation before the patient is brought in.

3.4. Amputated part status and advising the patient

This step determines the surgical strategy and the priorities. It depends on how many fingers are amputated, whether the thumb is amputated, and what is the macroscopic and microscopic state of the fragments. The surgeon then discusses possible options with the patient and secures his/he approval, while considering age, medical history and profession. This step is very important, as the recovery phase can be long with high functional consequences. A calm and confident relationship must be initiated by the surgeon. Following this discussion, the anesthetist performs the upper extremity block for the benefit of sympathetic blockade and subsequent vasodilatation. Non-surgical factors must be considered in the replantation decision especially psychiatric disorders which have been found to be correlated with poor outcomes and survival rates [21].

The amputated part is irrigated and washed carefully with saline solution without colored antiseptic. Direct visual inspection of the amputated part under magnification and radiographs of the bone damage are essential to determining the type of the injury and distinguishing between guillotine, crush or avulsion trauma. The most favorable case is the guillotine mechanism, as it produces less vessel and tissue damage and thus entails less debridement. Crushing rarely occurs with cutting machines and tools. Crushing damage can be tiered and affect the bones, blood vessels and nerves to different degrees requiring more extensive debridement. The avulsion mechanism, which often occurs in ring fingers, includes extensive damage to all the tendons, bones, blood vessels and nerves and requires very specific and aggressive debridement as explained further on.

Clinical examination of the skin can reveal a ‘‘red line sign’’ or a ‘‘blue ribbon sign’’ with pulp ecchymosis indicating severe shearing forces along the neurovascular bundle with extensive vascular injury, which requires extensive vascular debridement and may temper the replantation indication [22].

The amputated part is prepared under a magnifying loupe for skin debridement and the bone status is determined. Mediolateral incisions are made, and the skins flaps are secured using 5-0 nylon sutures. A magnifying loupe is used to view more proximal amputated parts or a microscope for smaller parts, such as preparing the distal phalanx arteries. Veins and nerves are tagged using 9-0 nylon leaving a 1 cm long tail for easy secondary identification.

Locating the dorsal veins requires caution during dorsal debridement to avoid damaging them; if too difficult, it should be done when the tourniquet is released, when blood flow is restored.

Digit irrigation with heparin solution is not performed in every case [23,24]. Most authors stress that inserting a catheter into the lumen of the vessels of the severed part damages the intima. Tamai et al. also showed that in the case of crush amputations, the amount of remaining blood was approximately twice as much as in clean amputations, with microthrombi and tissue emboli seen mainly in veins of crush amputations. They proposed irrigating crushed and avulsed digits prior to replantation [23]. According to FESUM surveys, only 40% of French hand surgeons perform finger irrigation [24]. We recommend finger irrigation using a 24-gauge yellow catheter without cutting its end, as this makes the plastic catheter sharp and damages the intima.

Bone resection, especially in the case of crush injuries, is then performed to avoid damaging the blood vessels and adjacent structures. Optimal skeletal shortening is important to ensure that blood vessels and soft tissue structures are nearly tension-free, essentially in the diaphysis area. Then the bone can also be shortened if arthrodesis will be required. This is most common in distal replantation. Most often K-wires are used and inserted in the amputated part under fluoroscopy guidance.

The distal part of a Tsuge suture or Kessler 4-strand core suture is placed in the flexor digitorum profundus, which is favored. Repair of the flexor digitorum superficialis (FDS) is often omitted in digit replantation in the interest of expediency, especially since it does not improve final function.

4. Surgical phase

4.1. Debridement

Both preparation of the amputated part and debridement of the hand help to predict and plan the subsequent replantation steps.

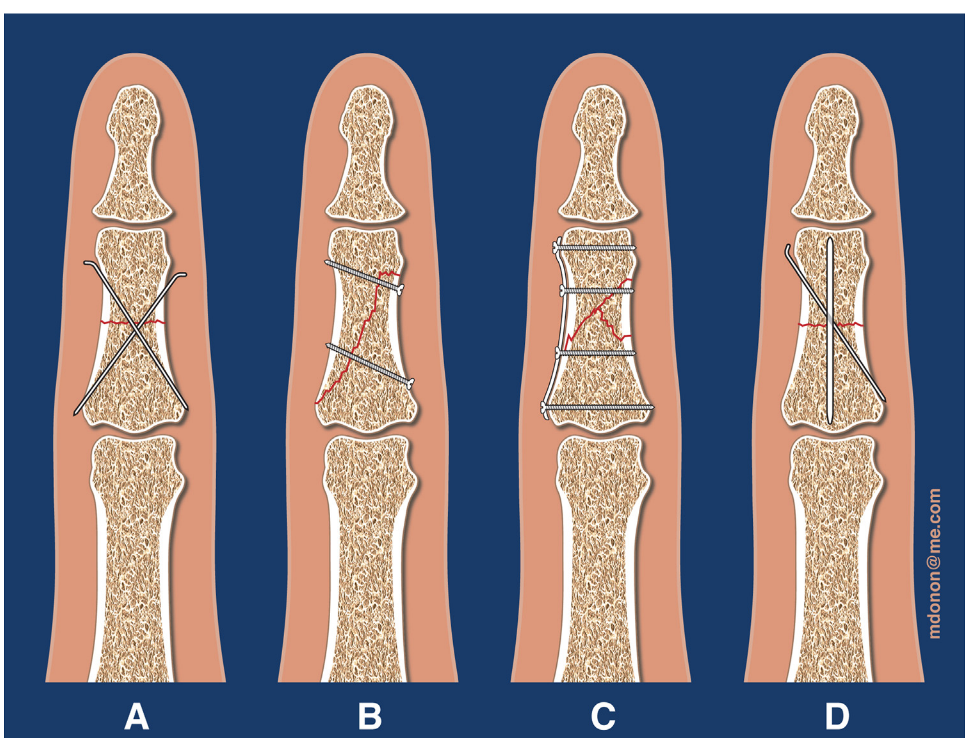


Fig. 2. Bone stabilization: K-wires (A); screws (B); plate (C); bilboquet (D).

The appropriate use of tourniquet time is paramount to efficient replantation. Firstly, debridement of the hand is made while the tourniquet is inflated and must be as fast as the surgeon's experience allows. This first tourniquet run is mostly required for vasculature examination and to determine how much debridement is needed, in case of crush or avulsion mechanism, and the potential need for vein grafts. If the "red line sign" is present, it often underlies a convoluted arterial segment that requires resection due to intimal disruption. If there is any doubt, then inflow is checked by deflating the tourniquet to ensure adequate flow. In this case, the next two steps of the replantation fixation and extensor tendon repair can be performed without the tourniquet inflated, especially in the setting of a multidigit replantation.

4.2. Bone and tendon repair

Bone preparation involves inserting K-wires initially into the amputated part using a back and forth motion, leaving free the PIP joint. In the mid-diaphyseal area, the use of a bilboquet device helps with stability and saves time especially in transmetacarpal and multiple digit amputations. This procedure can also be done using plate and screw constructs; however, the former technique is preferred to save time (Fig. 2). Following bone stabilization, the extensor tendons are repaired with PDS® suture. The dorsal veins are easier to locate now since the tourniquet is not inflated. Most commonly, the tourniquet is inflated to continue with flexor tendon repair, using Tsuge or Kessler suture with microsurgical instruments to manipulate the tendon parts as gently as possible.

4.3. Microsurgical steps

This usually occupies a large portion of the operating time in finger replantation cases. The set-up of the surgeon and surgical field are crucial for saving time.

4.3.1. Arterial repair

Direct arterial anastomosis of the digit's dominant artery (ulnar artery for the thumb, index and middle finger, and radial for the ring and little finger) is recommended even with a cross arterial direct anastomosis (Fig. 3). Sometimes a vein graft is required due to the extent of arterial damage and length of resection due to intimal damage. A vein graft taken at the distal volar forearm needs to be returned and irrigated before intercalated suturing. Attention must be paid to the vein graft having the correct radius to avoid asymmetrical size mismatch although principles of vascular surgery can be applied through an oblique cut of the arterial stump when there are different outer diameters. This technique increases the risk of flow turbulences as shown by Biemer [25,26]. The use of a vein graft increases the rate of revascularization success compared to primary suturing in cases of arterial loss [27–30] (Fig. 4). The vein graft's length must be carefully planned to avoid an overly long graft that results in kinking, which can cause turbulent flow and thrombosis (Fig. 5). More rarely, venae comitantes of the radial artery at the wrist should be considered since their diameter is constant, but they are rarely used in practice.

Although various microvascular anastomosis techniques include suture-less anastomosis such as laser-assisted microanastomosis (LAMA) [31] or fibrin-glue anastomosis [32], arterial anastomosis is generally performed using interrupted 10-0 nylon sutures at the finger area or 11-0 for distal amputations with the use of Tamai's disposable double plastic microclips or a Ikuta retractor. For distal anastomosis, free clamp sutures can be performed for the central pulp artery as part of the so-called "first back wall repair" [33].

In our experience, in order to decrease the risk of transfixation sutures, we use a looping type suture on the last two to three sutures. The needle and suture are passed two or three times without cutting the suture in order to leave the anastomosis lumen open (Fig. 6).

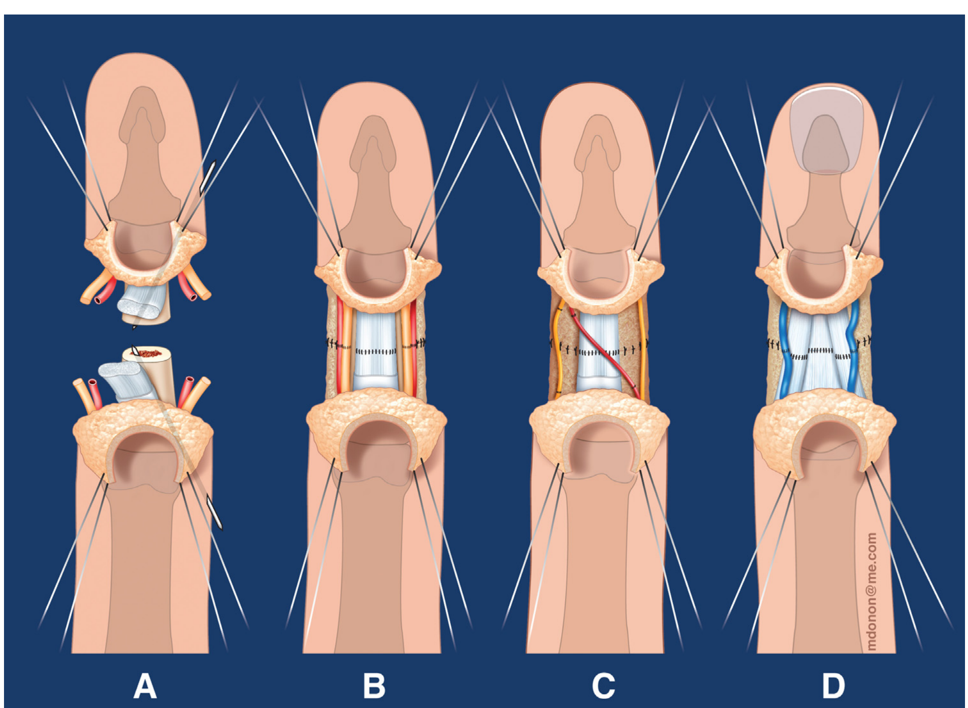


Fig. 3. Blood vessel repair: Parts preparation (A). Direct arterial anastomoses (B). Cross arterial anastomosis (C). Dorsal venous anastomoses (D).

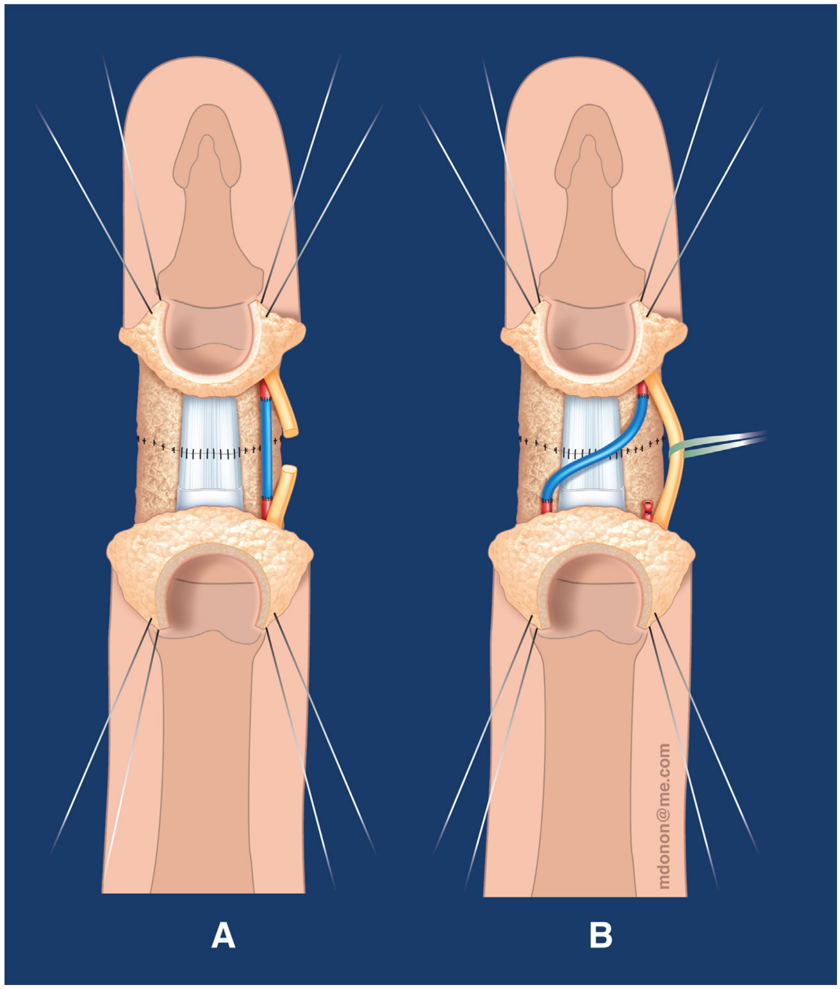


Fig. 4. Vein graft for arterial reconstruction: direct repair (A); cross repair (B).

When multiple finger replantation is performed, the tourniquet may be deflated and re-inflated to assist with the remnant arterial anastomosis.

4.3.2. Nerve repair

Nerve repair is a critical component of the procedure, the success of which may affect the finger or thumb's long-term function. In the 2000–2010 decade, as many articles on peripheral nerve repair techniques were published as in the entire preceding half century (1950–2000) [34]. Direct nerve suture is always recommended. When tension-free neurorrhaphy is not possible, nerve grafts are often required. Options include vein conduits for defects of less than 2–3 cm or absorbable nerve guides mainly in proximal hand amputations or transmetacarpal amputations. We do not consider these options necessary in addition to direct nerve suture, as they cause delays. In our experience, the new generation of essentially synthetic neurotubes cause major inflammatory reactions and discomfort in the thumb or finger area [35]. Autograft options include medial antebrachial cutaneous nerve, posterior interosseous nerve or nerves harvested from spare parts in the case of multiple finger amputation, which is known as the ''spare-parts'' (finger bank) concept [36].

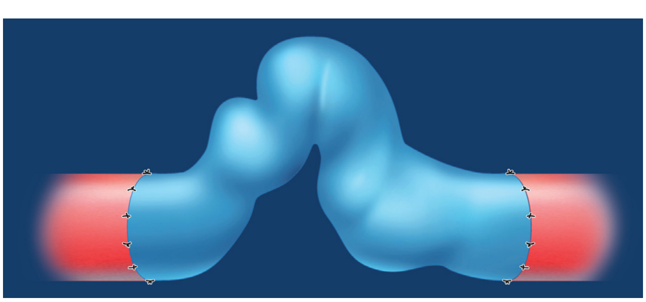


Fig. 5. Kinking phenomenon in vein.

4.3.3. Venous repair

When possible, venous anastomoses are performed while the tourniquet remains inflated. In distal replantation the tourniquet can be released to help with vein distension and location, and re-inflated to perform the venous anastomoses. Two veins for one artery are required to ensure optimal venous drainage and decrease the risk of thrombosis [37] (Fig. 3). Venous grafting will be required if no direct anastomosis is possible.

4.3.4. Skin closure

The tourniquet is deflated to check blood vessel anastomosis through a patency test and the condition of any vein grafts, especially as they distend, often significantly. Papaverine with serum can be used for digit vasodilatation. Coloration is confirmed. Bipolar coagulation precedes skin closure which is performed without any tension. Full thickness skin grafts can be used for resurfacing directly on veins or grafted veins on the dorsal aspect of the digit.

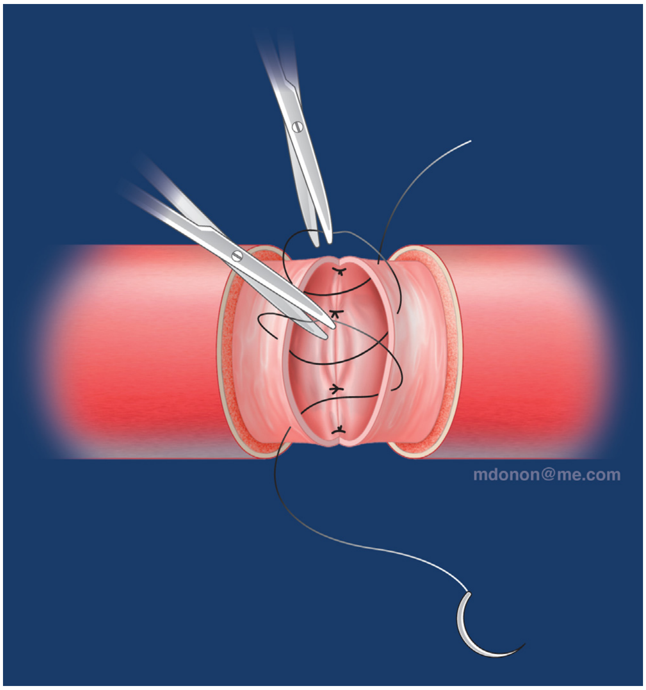


Fig. 6. Looping-type suture.

4.3.5. Dressing

The dressing application is an important step in the procedure and is done by surgeon. This task should not be delegated. Paraffin gauze dressings are applied in a linear and non-circular fashion as are the compresses. A splint is made to keep the hand and replanted digits secure avoiding any untimely motion and leaving the pulp free for examination.

4.3.6. Postoperative care protocol

Clinical examination to evaluate temperature, finger pulp color and edema with capillary refill performed hourly in the first 12 hours and thereafter, every 2 hours for the next 72 hours, per hand surgery protocols. Examinations are performed by trained nursing staff and recorded on the patient's record. The use of warming agents such as heating lamps is discouraged as there is no evidence it improves the success rate of microsurgical procedures [38].

Smoking should be prohibited to guarantee optimal circulation [39,40]. However a recent meta-analysis did not find a significant effect of smoking on finger or thumb survival rate [21].

A personalized relationship of trust is needed between the patient and the surgeon who is the preferred point-person for the follow-up.

5. Complications and immediate postoperative pharmacologic and environmental support

5.1. Complications

The most common complications are arterial and venous thrombosis. Venous thrombosis is the primary reason why replantation fails. Arterial thrombosis is three times as common as venous ones but has a better outcome. The salvage rate of digit replantation complicated by arterial thrombosis is 30%, whereas it is only 7% for venous occlusion [41,42]. The risk for thrombosis is highest (80%) during the first 2 postoperative days and decreases to 10% after postoperative day 3. This risk pattern is attributed to the initially low flow volume through the pedicle.

Experienced clinical staff can evaluate the arterial or venous origin of the affected digit. The early onset of venous congestion can be elicited by the "throbbing sign" described by Leung, even before any obvious color changes: "It is elicited by pinching the digit between the thumb and finger of the examiner until the skin blanches. Releasing the pressure slowly, a sensation of throbbing will be felt synchronous with the patient's pulse rate" [43].

The first step is removing the dressing, splint, and finally the skin sutures to release any extrinsic compression. If the status worsens or does not resolve, the patient may be returned to the OR for exploration. Likely revision of the anastomosis will be performed to salvage the digit. This is typically accomplished with resection of the thrombosed area with subsequent primary anastomosis or vein graft. The use of intravascular pharmacologic thrombolysis with agents such as streptokinase or urokinase are options to increase the salvage success rate [44]. However, it is not routinely recommended due to limited evidence.

5.2. Pharmacological support

Platelet aggregation is the underlying cause of arterial thrombosis whereas venous thrombosis is primarily the result of fibrin clotting, theoretically making aspirin the preferred agent for arterial thrombosis and heparin the better anticoagulant for venous thrombosis [45].

The appropriate timing of anticoagulation therapy maximizes its effectiveness. The first 2 days after surgery are crucial because most of the clots form during this time. Aspirin is widely used [24,46]. The bleeding risk is dose-dependent and a low dose regimen (75 mg/kg) minimizes this risk [46]. As such, the standard dose is 160 mg per day for adults and is to be continued for 15 to 30 days depending on the surgeon's preference. Low-molecular-weight heparin (LMWH) is administered during the recovery phase at a prophylactic dosage. The vasodilation effect of heparin may reduce thrombosis further by increasing the blood flow rate [47]. The data from Khoury et al. suggests that subcutaneous heparin is the only anticoagulation method that is statistically significantly associated with decreased odds of thrombosis [48].

Dextran has been used because its antithrombotic effect is mediated by a reduction of erythrocyte aggregation and platelet adhesiveness. The increased risk of complications, such anaphylaxis, acute renal failure or cerebral edema with dextran, makes it an unattractive candidate for routine thromboprophylaxis.

Although anticoagulant therapy is a part of replantation surgery, anticoagulation protocols vary widely among microsurgeons. Therefore, current recommendations for microsurgical anticoagulation therapy are based on an extrapolation of conflicting animal data and scant human studies [49]. The importance of salvaging a replanted finger must be weighed against the risk of a blood transfusion. A single-agent (heparin or dextran) regimen, in addition to aspirin, was associated with an average 6% drop in hematocrit and a 2% blood transfusion rate. Multiple-agent (triple) therapy produced an average 15% drop in hematocrit and blood transfusion rate of 53% [50]. We do not recommend combining three agents. We recommend aspirin for 15 days associated with LMWH in prophylactic doses during the recovery phase with a platelet function assay.

Medicinal leeches relieve venous congestion both actively, as a result of the bloodletting action, and passively, by direct injection of hirudin into the host from within the leech saliva that is more potent than heparin [47,51]. Leech therapy has mostly been used after very distal replantation and is reported to have a high salvage rate [52,53]. More recent publications indicate that use of leeches

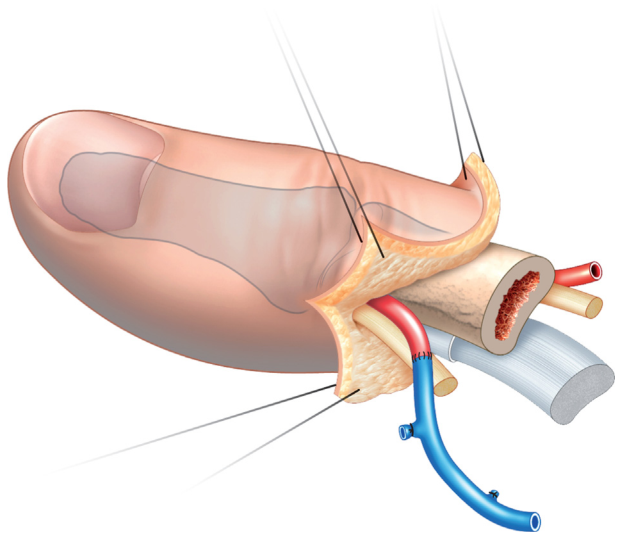


Fig. 7. Preplacement venous graft in thumb replantation.

for 4½ days seems to lead to a higher rate of finger survival but increases the rate of blood transfusions as well, up to 57% [54,55]. We do not recommend using leeches for more than 3 days and mainly for distal replantations.

6. Indications

6.1. Thumb

The thumb is the guest star of replantation and it is probably for that reason that the first digital replantation using microvascular techniques was that of a completely amputated thumb, by Komatsu and Tamai in 1968 [4].

Since then, there is a strong consensus in favor of thumb replantation regardless of age, mechanism and condition of the amputated part, as the overall function of the replanted thumb is mostly good when compared to the poor overall hand function when missing a thumb [56–59]. The most commonly used classification of thumb amputation is the Merle classification [60].

The particularity of the human thumb position, out of the finger plane, makes the performance of arterial reconstruction difficult. The injured hand must be held in maximum supination with wrist flexion facilitated by the Tupper hand retractor; however it remains uncomfortable for the duration of microsurgery replantation. Because of the difficulty of exposing the proximal arterial stumps, even more so after debridement, vein grafts are often used in thumb replantation. The preplacement of venous interposition graft to the digital artery stumps in the amputated thumb prior to bone fixation improves the patency rate and the ischemia time [61] (Fig. 7).

After amputation and reattachment, proximal anastomosis is performed at the radial artery with a short exposure at the anatomical snuffbox under the EPL, which is a good location to access the radial artery (Fig. 8). In multiple digit amputations, the notion of spare parts (finger bank) is most relevant in the case of an amputated (and missing) thumb or when the thumb is not replantable due to extensive damage. In this case, the least damaged digit is replanted in transpositional digital microsurgery to act as a thumb.

6.2. Distal replantation

With the advancement of microsurgical techniques, single finger amputation distal to the FDS insertion and fingertip amputations are now considered a good indication for replantation since the cosmetic and functional outcomes are good [52,62,63] (Fig. 8).

Several classifications have been proposed for distal digital replantation [64]. The Ishikawa classification is widely used, as it predetermines the possibility of repairing both an artery and a vein and whether venous outflow anastomosis will be needed [65] (Fig. 9). Indeed, the success rates of amputations distal to the DIP joint have been reported to be between 70% and 90% when an artery and vein are repaired [64].

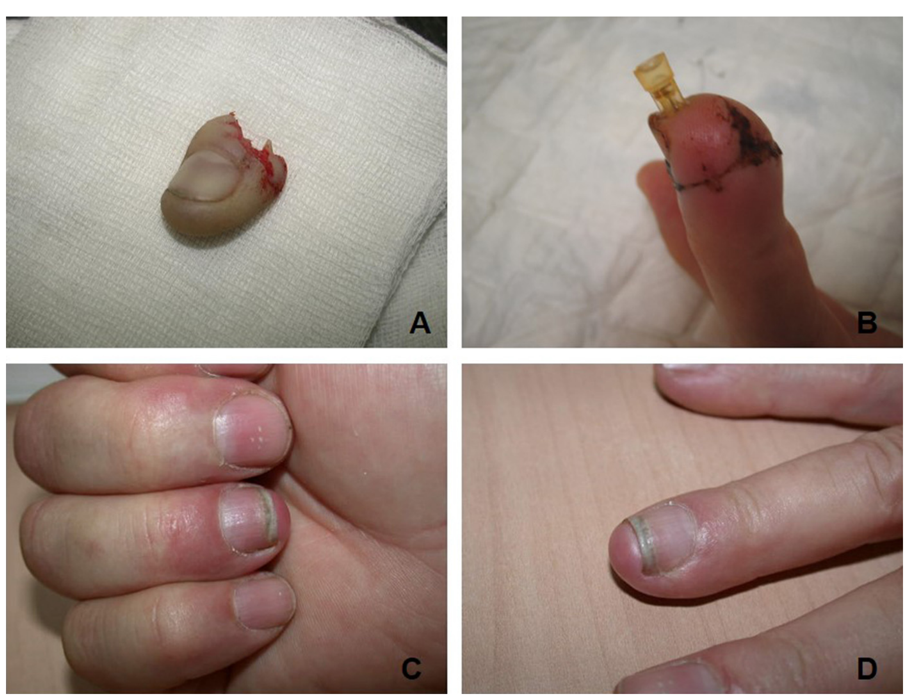
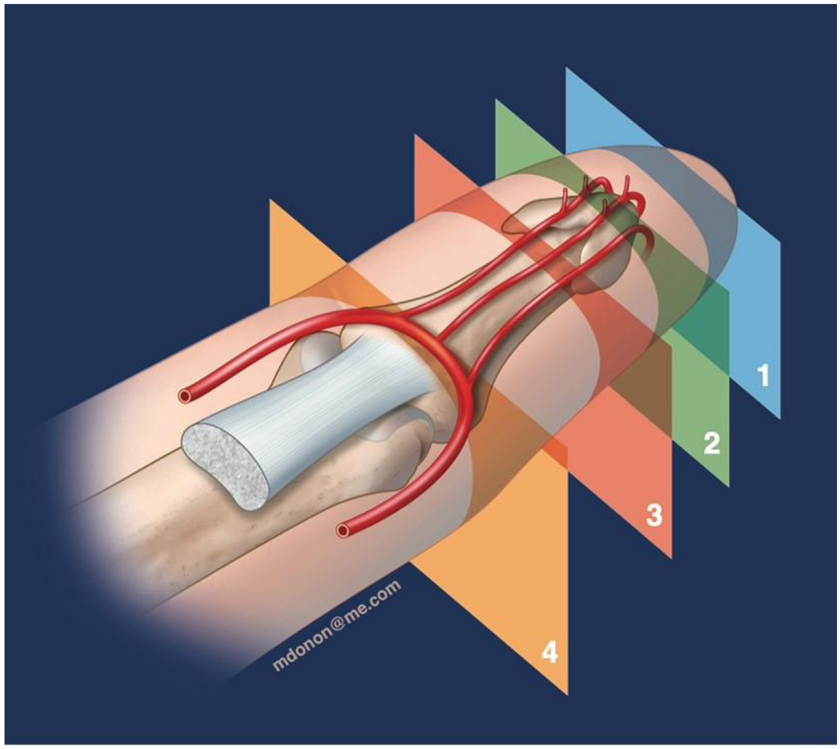


Fig. 8. Distal amputation: preoperative condition (A); postoperative view (B); final functional and cosmetic results (C, D).



	Bone	Artery	Vein	Nerve
1	-	-	-	-
2	-	1	-	-
3	K wire	1	Dorsal/Palmar[a]	1 - 2
4	DIPJ fusion	1 - 2	Dorsal	2

[a] Zhang [69] or Suzuki [65] technique can be considered; DIPJ: Distal Interphalangeal Joint

Fig. 9. The Ishikawa classification for distal amputations and applications to blood vessel and nerve repair.

The surgical procedures are carried out simultaneously on the amputated part and on the finger (Fig. 10). The bone fixation is simpler in distal amputation as an axial K-wire or needle is sufficient to assure skeletal stability. Two oblique skin incisions are made on the palmar surface, and triangular flaps are elevated, as described by Tsai et al, in order to facilitate the exposure [66]. The distal arterioles deriving from the distal arch of the digital arteries (size: 0.85 ± 0.1 mm) are selected. The so-called pulp central artery is commonly used for anastomosis, even more so with the detour of this arcade to increase the length in case of artery defect and favor end-to-end anastomosis, in order to avoid a venous graft in this minuscule environment [67].

Ultra-microsurgical techniques involve a vascular anastomosis of less than 0.5 mm with four to six suture points using 11-0 nylon with a 50 μm needle. At this level, microclamps are useless, and a first back wall repair is usually performed. In zones 3 and 4, a dorsal terminal vein can usually be anastomosed. It is approximately 1 mm at the DIP joint [68].

The option to forego venous anastomosis may not exist when the amputation is more distal to zone 3 and the DIP joint. However, replantation distal to the DIP joint makes it difficult to find a suitable drainage vein in the amputated part. If two arteries are available at this level, the following options can satisfy outflow from artery-only replants:

- the use of an arteriovenous fistulae in place of venous drainage by anastomosing a second available digital artery to a palmar vein [65];
- the Zhang technique, which consists in anastomosing the two arteries and ligating the larger one proximal to the DIP joint. Ligation of the artery proximal to the recurrent vessels stops blood flow from the body. Thus, the outflow continues through arteriovenous communication and recurrent vessels to the dorsal digital veins [69].

If no vein can be repaired, the procedure is referred to as an artery-only replantation. Finally, if nerve repair cannot be done as we reach the tuft level, then nerve transfer will be required to ensure sensory recovery [70].

The skin closure requires particular attention. We de-epidermize the stump skin of the amputated part and the proximal digit bank over 1–2 mm each. Closure is then performed, overlaying the two de-epidermized surfaces. This increases the cutaneous surface contact and the venous neo-connections (Fig. 10F).

When no venous drainage is available, controlled bleeding is initiated as soon as the surgery ends. We create an incision in the distal pulp to allow for venous egress; heparin scrubs are performed at the bedside every hour. Using leeches can help in case of venous congestion. This controlled bleeding is associated

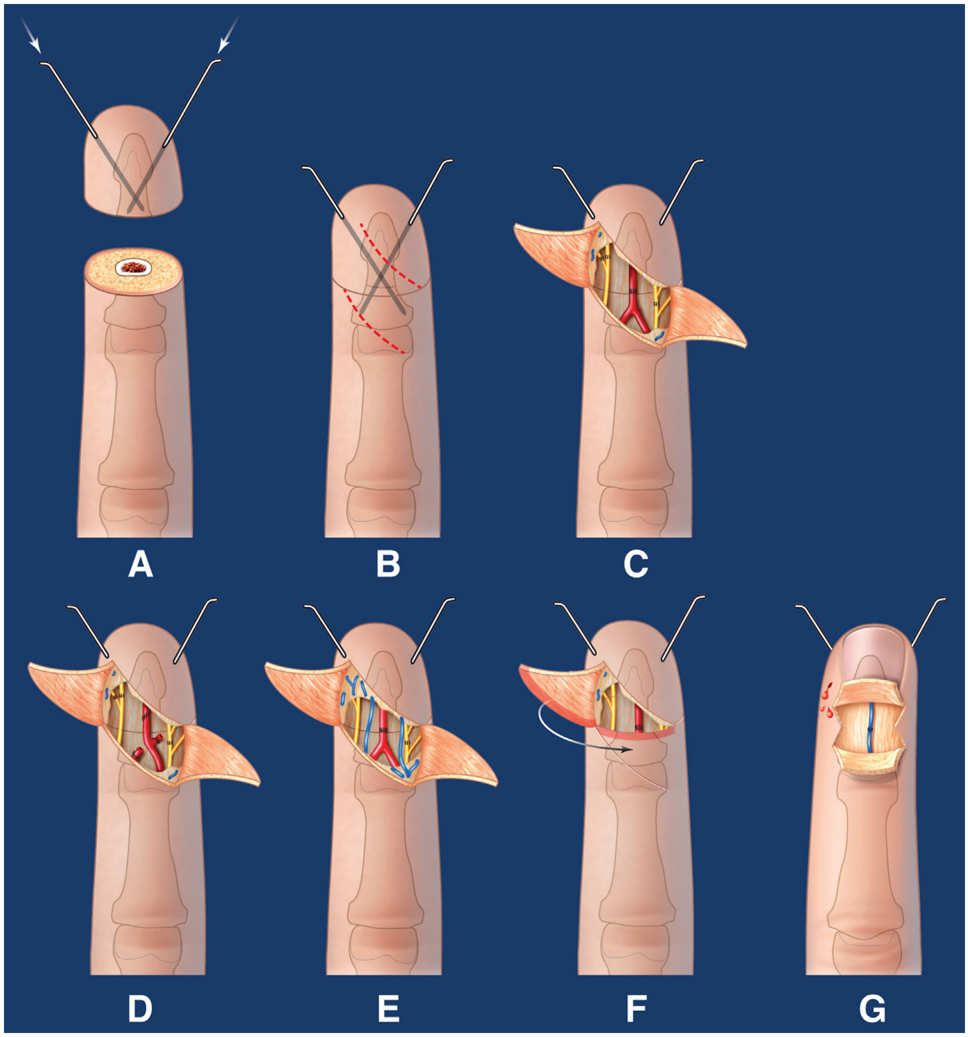


Fig. 10. Distal replantation: replantation preparation (A); oblique skin incisions for larger exposure (B); central artery pulp anastomosis (C) with the detour of this arcade to increase length and favor end-to-end anastomosis (D); palmar vein anastomosis (E); closure overlaying the two de-epidermized surfaces (F); dorsal vein anastomosis in zone 3 and 4 (G).

with an anticoagulation protocol. Four to six days is required for intrinsic venous outflow.

6.3. Digit avulsion

Replantation of a complete ring finger avulsion has been debated and long considered a flawed treatment choice due to poor functional results [71–74]. This represents a serious reconstruction challenge for the hand surgeon. Existing classification systems specify which elements condition the functional prognosis and have expanded the indications for replantation [71,75–78]. We use the Urbaniak [71] classification revised by Kay et al. [77] and subdivision of the class IV according to Adani et al. [75] (Table 1). The replantation technique has been described well by Foucher et al. [27]. We would like to offer the following tips (Fig. 11).

After debridement of the damaged tissues, the palmar proper digital artery is exposed using a short hemi-Bruner incision at the DIP joint on the dominant vascular side, while avoiding splitting the sheath. It is important to spare the contralateral artery; otherwise transverse anastomotic arterial network will not allow reverse contralateral perfusion. This cutaneous transverse anastomotic pattern has already been studied [79].

The bone fixation phase can be difficult as extreme caution is required on the digital sheath. Most of the time, DIP arthrodesis is performed using protective intramuscular needle cap to avoid traumatic dissection of the distal phalanx. The K-wires are inserted using a back and forth motion through the needle cap to achieve DIP fixation [80].

The choice between direct anastomosis and the use of a vein graft for arterial repair is made after microscopic examination of the proximal stump artery and when a proximal arterial thrombosis exceeds 1 cm. The use of a vein graft increases the rate of revascularization success compared to primary suturing [28–30,80–84]. Following distal anastomosis of the vein graft, the subcutaneous passage of the vein and repositioning of the degloving part is facilitated by using sterile liquid Vaseline. The proximal anastomosis is performed close to the common palmar digital artery bifurcation where the microscopic conditions are better. Nerve repair is often difficult due to the stretching injury. In our practice, the proximal dominant stretched nerve is inserted distally in the sheath in a nerve transfer procedure. Taking a nerve graft from an uninjured site is not recommended.

The key to maximum functional recovery is having the patient mobilize the functional and uninjured PIP joint by themselves right away [80].

Table 1
Classification of ring finger injuries: Urbaniak [71] revised by Kay et al. [77] and subdivision of the class IV injuries according to Adani et al. [75].

Stage	Description
I	Circulation adequate with or without skeletal injury
II	Circulation inadequate, no skeletal injury
IIA	Arterial circulation inadequate only
IIB	Venous circulation inadequate only
III	Circulation inadequate with fracture or joint injury present
IIIA	Arterial circulation inadequate only
IIIB	Venous circulation inadequate only
IV	Complete amputation
IVd	Amputation distal to the FDS insertion
IVp	Amputation proximal to the FDS insertion

FDS: flexor digitorum superficialis.

Primary resection has been recommended by a few authors [72–74]. We think it is judicious to discuss amputation in a second procedure, after some time has elapsed, following the initial microsurgical management, in order to ensure patient consent.

Preventing ring avulsion injuries has been advocated and several devices to pre-weaken rings have been developed to make them less traumatic [85]. Prevention should not be limited to awareness but should also include introduction of and adherence to manufacturing standards [86].

According to the different classifications and authors, the indication for replantation of complete ring fingers are essentially those distal at the FDS insertion and mostly the DIP joints. Without obfuscating the moral harm that can be caused by the loss of a finger in a young adult, replantation in case of proximal avulsion–especially with PIP dislocation–does not lead to a reasonable functional outcome despite the vascular success. The surgeon's and patient's motivation must be considered. The functional and cosmetic outcomes are also dependent on postoperative care and management (Fig. 12).

6.4. Skin defect management

When soft tissue defects lead to blood vessel or bone exposure, especially on the dorsal aspect of the replanted finger, use of

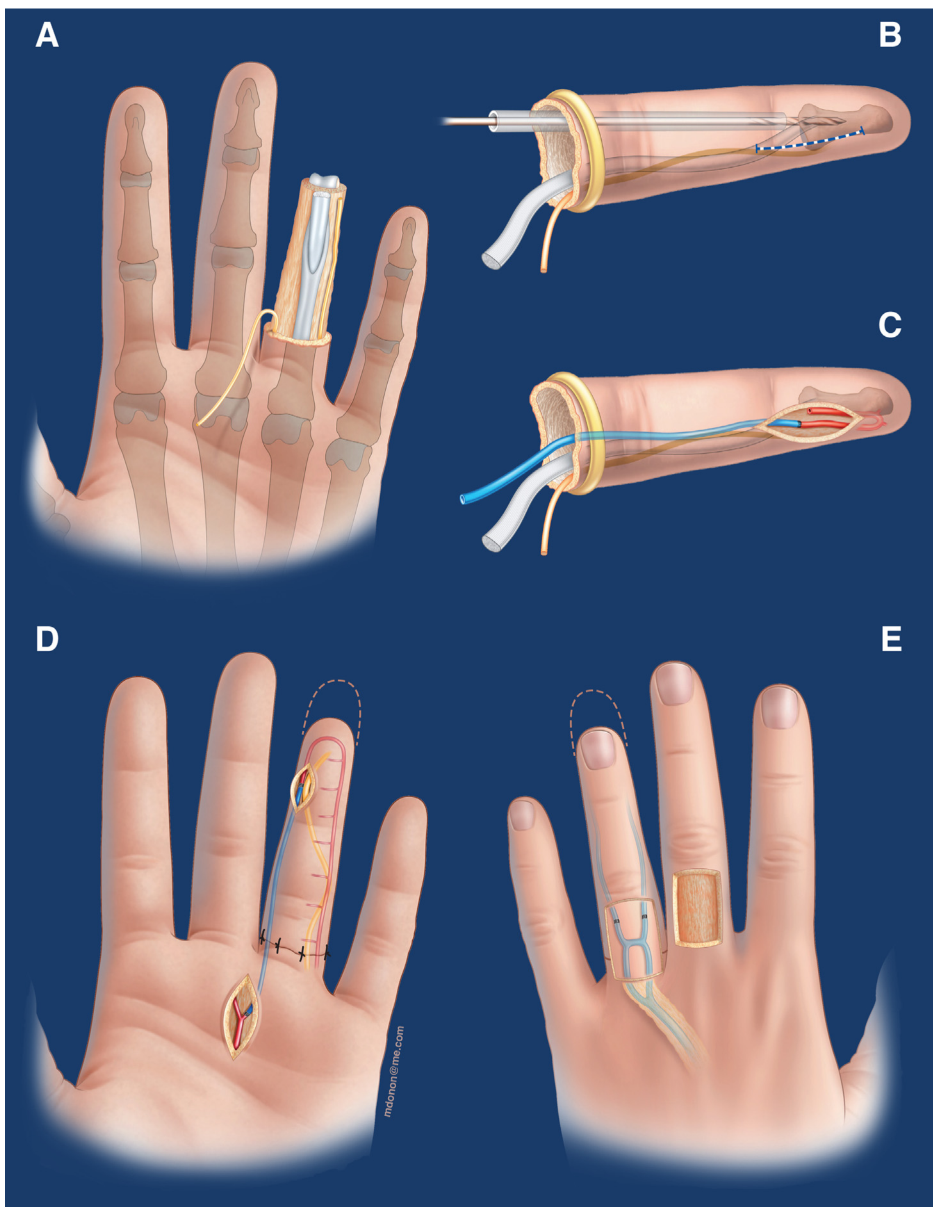


Fig. 11. Ring finger avulsion: preoperative status (A); distal artery exposure and preparation for bone fixation (B); prior distal vein graft anastomosis (C); replantation and proximal artery anastomosis (D); flag flap for skin coverage and venous flow restoration (E).

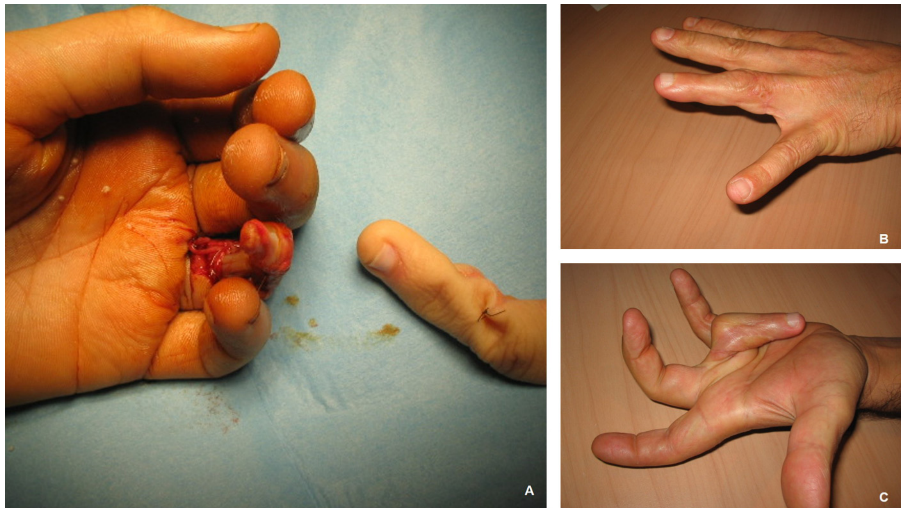


Fig. 12. Ring finger avulsion: preoperative view (A); final outcome (B, C).

cutaneous venous flaps have been promoted for tissue coverage, as well as venous repair for outflow restoration. For the thumb, we recommend using the kite flap described by Foucher [87] (Fig. 13) and Vilain's flag flap [88] for the other digits in ring finger avulsion (Fig. 11E). Both flaps require only one end-to-end anastomosis for the venous drainage. In case of a dorsal defect, the use of a dorsal flag flap from the adjacent digit should be considered to bring soft tissues and a vein graft to the site.

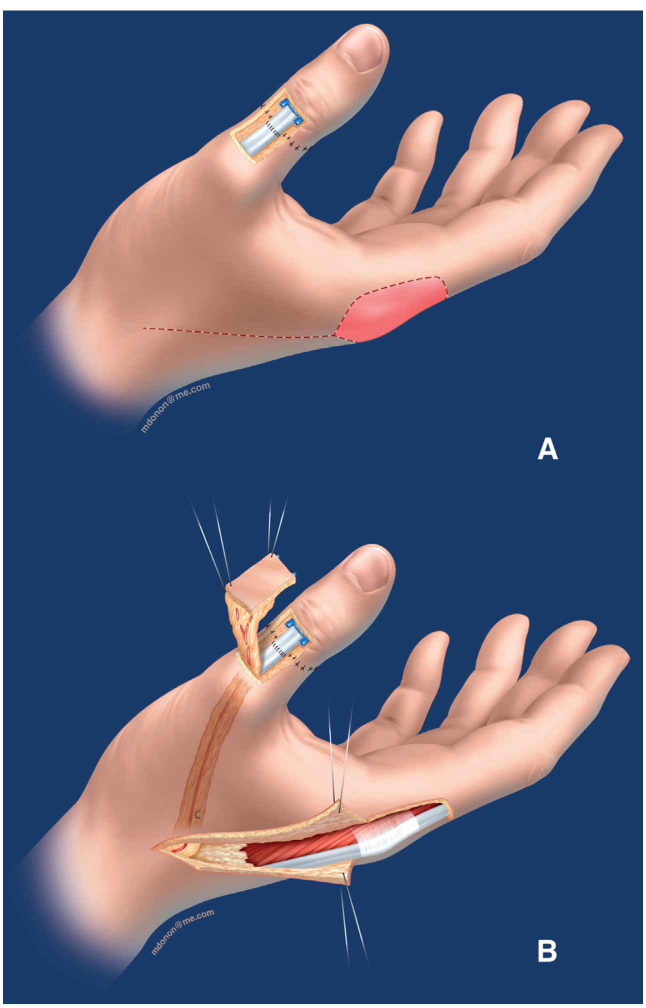


Fig. 13. Venous kite flap for dorsal loss skin of the thumb (donor site) (A). Dorsal venous flow restoration (B).

Free cutaneous venous flaps were first taken from the dorsal skin of the foot [89]. Later, the dorsal aspect of an uninjured digit was used, increasing the survival rate of the flap when compared to the forearm donor site [90]. The venous free flap is more commonly used to reconstruct segmental defects in the digital artery and for palmar simultaneous soft tissue coverage [91]. However, they have two main disadvantages: they can be a time-consuming part of the operation as they require an entirely new microsurgical procedure and they are not superior to pedicle flaps as previously described, at least in the proximal part of the finger.

6.5. Transmetacarpal replantation

This challenging injury is different from more proximal or distal injuries because the lumbrical and interosseous muscles lie within the injury zone. A high rate of finger survival following transmetacarpal replantation has been shown. However, ischemia of the intrinsic muscles plays a key role in the poor functional results. The earliest descriptions of blood supply to the intrinsic muscles [92,93] show that the lumbricals receive blood supply from both the deep and superficial palmar arches.

To restore maximum blood flow, one should perform multiple vein grafts on all available distal arteries. This can be made by direct VY vein graft (Fig. 14) or by using the dorsal venous arches of the foot [94]. The potency of one common digital vessel alone can provide blood flow to all fingers through transverse and commissural vessels connecting the digital vessels proximal to the interphalangeal joints (Fig. 15). Retrograde flow to the adjacent common digital vessels revascularizes the other digits [95,96].

Despite successful revascularization of the fingers, the intrinsic muscles are left ischemic in the "middle ground" in the palm of the hand with resultant sclerosis and contracture. Resection of the involved intrinsic musculature and sufficient metacarpal shortening (at least 12 mm) should be considered [97].

6.6. Multi-digit amputations

Such dramatic injuries require high-level and immediate decision making in order to maximize the functional outcome. The essential procedural steps to be followed are:

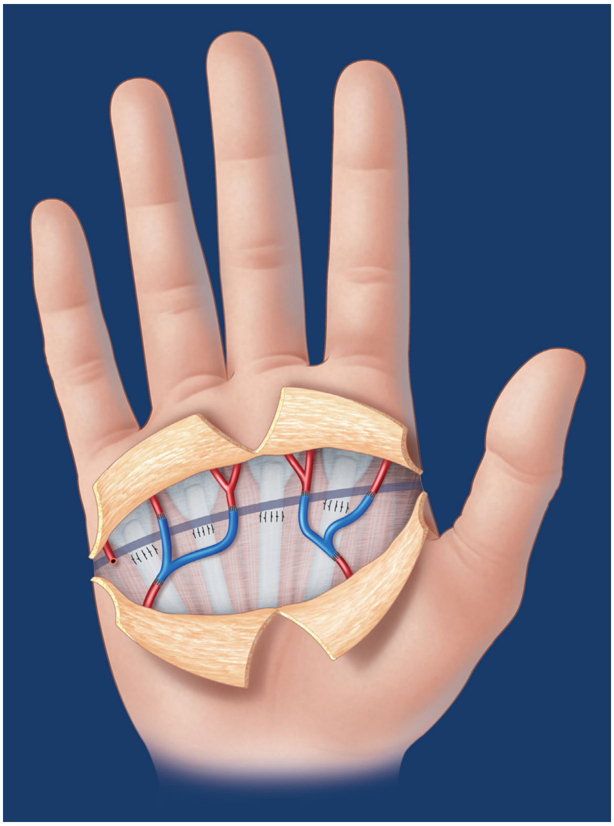


Fig. 14. Restoration of transmetacarpal arterial flow by direct VY venous graft.

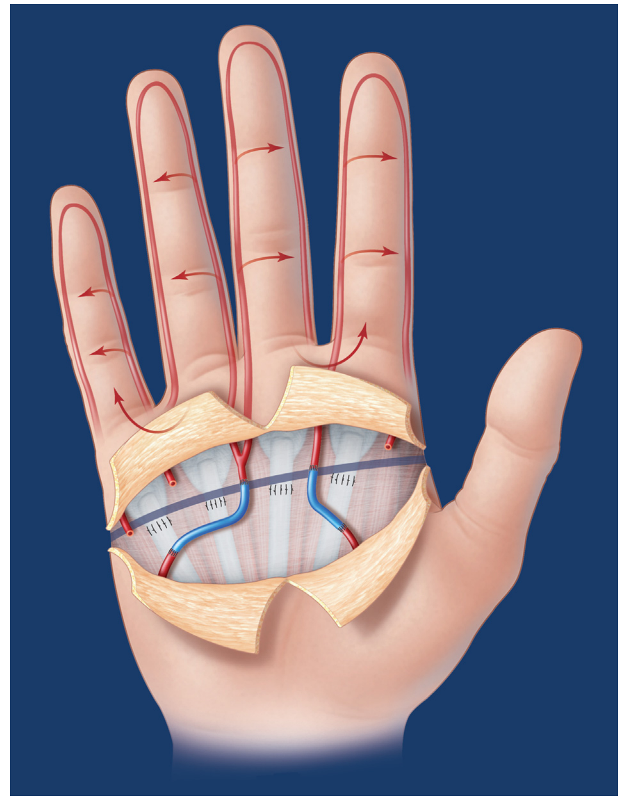


Fig. 15. Restoration of blood flow using a single artery digit through digital transverse and commissural vessels.

- team concept for strategic decision-making and multiple surgeons for simultaneous surgery [98,99]. Depending on the surgeon's preference and situation, either a synchronous or sequential technique can be used, with the latter being most commonly practiced today [100];
- creative use of the spare parts bank to improve priority digit replantation [36,101];
- digit transposition allows the most usable part to be placed in the most effective position;
- replantation priorities: the highest priority is salvaging the thumb, which opens to door to creativity, from the amputated thumb part to the use of spare parts and finally digit transposition.

At this point of the decision-making process, it is important to understand that each patient is an individual case. The number of digits useful for replantation drives the process along with finding a functional balance between reconstructing the radial aspect of the hand (emphasizing the two or three-point pinch grip) to the reconstructing the ulnar side (emphasizing the power grasp). In any case, the index position is of the least importance.

7. Conclusion

A finger or thumb replantation procedure is a moral contract between the surgeon and his patient, from the initial surgical indication to postoperative care and management. Whether the surgeon is faced with a single- or multi-finger amputation, it is essential to follow established guidelines to optimize the operative and postoperative stages. Table 2 summarizes the workflow to achieve the best functional and cosmetic outcome while also being time-efficient.

Table 2
Summary of suggested workflow to optimize time efficiency in digit replantations.

	Basic	Thumb variation	Ring finger	Multi-digit and transmetacarpal
1	Bone fixation	Arterial graft on amputated part	Arterial graft on amputated part	Bone fixation
2	Extensor tendon repair	Bone fixation	Bone fixation	Extensor tendon repair
3	Flexor tendon repair	**Proximal arterial anastomosis**	**Proximal arterial anastomosis**	***Vein repair/ Venous flap***
4	**Arterial repair/reconstruction**	**Extensor tendon repair**	**Arterial repair/reconstruction**	***Flexor tendon repair***
5	**Nerve repair/reconstruction**	**Flexor tendon repair**	**Nerve repair/reconstruction**	***Arterial repair/reconstruction***
6	**Vein repair/reconstruction**	**Nerve repair/reconstruction**	**Vein repair/reconstruction**	***Nerve repair/reconstruction***
7	Skin closure	**Vein repair/Venous flap**	Skin closure	Skin closure
8	Dressing and splint	Skin closure	Dressing and splint	Dressing and splint
9		Dressing and splint		

Bold: one tourniquet run. Italics: one or more tourniquet runs.

Disclosure of interest

The authors declare that they have no competing interest.

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