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外傷性斷指再植之進階研究--
克服血管問題及簡化手術麻醉過程

Advanced Researches of Replantations for Digits Suffered from Traumatic Amputation-- Overcoming Vascular Difficulties and Simplifying Surgical Anesthesia

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口試委員會審定書

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本論文係 黃慧夫君（學號 D98421101）在國立臺灣大學臨床醫學研究所完成之博士學位論文，於民國 111 年 05 月 27 日承下列考試委員審查通過及口試及格，特此證明

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What does not kill me,

makes me ~~stronger~~ stranger.

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中文摘要

人類萬能而靈巧的雙手，創造了先進科技與高度文明的社會，幫助我們改善日常生活。 絕大多數生活上的工作，都需要倚賴雙手，尤其在視覺不良的情況下，往往更需要手部觸覺來輔助視覺，完成各式各樣的任務。 因此，我們的雙手是最常受傷的部位之一，也是醫院急診部門常見的求診原因。 這些手部的意外傷害，傷勢非常急迫而且十分疼痛，需要立即處理。 另一方面，手部的構造精細且複雜，修復手部外傷需要高超的顯微手術技巧，以及高度細心與耐心。

在手部外傷當中，以外傷性斷指或斷肢為最嚴重。 若沒有即時有效的處置，將會導致肢體永久缺損，嚴重影響手部的功能及外觀，進一步降低勞動力與生產力，對於家庭及社會的影響甚鉅。 回顧文獻報告，外傷性斷指嘗試手術接合率約略是 20%至30%。 意即大多數的斷指傷害，都放棄再植接回治療，進而喪失復原的機會。 探討放棄斷指再植的原因，包括：就醫可近性不足，醫療費用昂貴，手術過程困難且複雜，恢復期漫長，專科醫師人力缺乏與設備不足，醫療給付太低，醫師缺乏熱忱。 這些因素都是負面影響病患和外科醫師的接合斷指意願。 即使病患接受斷指再植接回，文獻報告的手指再植存活率差異頗大，約略是 30%至 90%。 差異如此大的原因，是斷指本質上的隨機性與高度不可預測性之傷害，再加上這類手術需要憑藉繁瑣的顯微縫合技巧與勞力密集的術後照顧。 因此，大多數的外科醫師不願投入這個領域，對於斷指再植手術避之唯恐不及。 身為整形外科醫師，我投入於醫治手部外傷已經累積二十年的經驗，專精於斷指再植手術。 這份論文的主軸，包含四個核心主題，循序漸進克服指尖的血管問題以及簡化手術麻醉過程，目標以增進斷指手術的嘗試接合率和手指存活率。

第一部分是探討外傷性指尖的再植手術。 由於遠端指節的解剖構造很精細，末梢血管分支的管徑非常細小，接合血管的顯微手術十分困難。 甚至在甲床附近缺乏合適的靜脈，因此，大多數的外科醫生顯然已經放棄了試圖指尖再植的所有努力。 我嘗試只有動脈吻合的指尖再植，其手指的存活率為 81.8%，並不遜於兼具動脈吻合和靜脈

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吻合的斷指再植之存活率。 然而，另一組無法接合動脈及靜脈之指尖再植，其手指的存活率為 0 %。 因此我得一個重要結論，末端指節的斷指再植存活率，並不必然需要靜脈的吻合，但是指尖動脈的吻合具有決定性的重要角色。 這部分的研究成果，鼓舞外科醫師盡量去嘗試遠端指節的斷指再植手術，即使是缺乏手指靜脈的吻合，也有不錯的手指存活率。

第二部分的研究是延續上一階段。 一般而言，常規的斷指再植手術通常兼具動脈吻合和靜脈吻合，重建斷指的血液循環。 然而，手術後偶而出現靜脈阻塞，導致手指充血腫脹的併發症，此時需要立即處置，否則該手指就會逐漸壞死。 傳統上，斷指再植術後出現靜脈阻塞，需要緊急安排再次手術，再一次重建靜脈管路，疏解充血現象。根據前一段成果，既然遠端指節的斷指再植，不需要依賴靜脈吻合，於是我採用放血治療挽救靜脈阻塞的方法。 臨床觀察比較這二組處置的手指存活率，竟發現放血治療效果優於再次手術效果的趨勢。 但是值得注意，放血治療承受較高的失血風險，需要接受較多的輸血量。 面對斷指再植術後發生靜脈不良的突發情況，我建立了一套治療策略，幫助臨床醫師篩選合適的病人接受合適的治療，以提升手指的存活率。 這部分的研究成果，幫助外科醫師有效處理再植術後靜脈阻塞，有效避免不必要的二次手術，減輕術後照顧的負擔，增進斷指挽救的成功率。

斷指的意外傷害，我們無法預測傷害發生的時間點和嚴重程度，病患和外科醫師常常需要緊急應變，以應付這個突發其來的意外狀況。 由於斷指再植的手術，必須要修補細小血管和神經的精密步驟，而且手術過程非常耗時，傳統上都是安排病患接受全身麻醉，以方便進行顯微手術的技術。 因此，為了全身麻醉的準備，病患在急診處等候的期間長久，增加傷口的疼痛與失血，也延長斷指的缺血時間。 為了克服上述的狀況，本論文第三部分的研究方向是採用局部麻醉來進行斷指再植手術，以減少等候時間和傷痛折磨。 在充分清醒的局部麻醉下，執行斷指再植的成功率是 81.25%，其不遜於全身麻醉下的斷指再植之存活率，並且有效縮短等候麻醉的準備時間。 根據我的經驗，為了順利完成充分清醒局部麻醉之斷指再植手術，篩選合適的病患是最重要的關鍵步驟。 我建議適合本術式的病患條件如下：1.斷面切口整齊的單支斷指，組織沒有粉碎壓砸傷害、2.預估手術時間小於三小時、3.病患心智成熟穩定，配合度良好可

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遵從醫囑，並且沒有危及生命之傷害。 這部分的研究成果，證明斷指再植手術可以在充分清醒局部麻醉之下順利進行，並縮短等待時間及等候焦慮，減少醫療依賴與需求，降低醫療花費。 這個簡化手術麻醉過程，可以幫助外科醫師和病患更容易更方便進行斷指再植手術，甚至進一步增進斷指結合的意願和嘗試接合率。

第四部分的內容是設立一個評估斷指傷害嚴重程度的分級標準。 回顧文獻報導，斷指傷害並沒有一個客觀的分級準則，傳統上只有大略區分成截斷傷、壓砸傷、或是撕脫傷。 然而，大多數的斷指傷害都是混和型外傷，嚴重性程度也參差不齊。 因此，我根據斷指修復的構造順序，依照外傷嚴重程度給予分級，愈嚴重的損傷相對應愈高的分數。 一個好的外傷分級系統，明確訂定各個組織損傷的嚴重程度，可以幫助醫師完整評估傷勢，詳細的醫療紀錄，並且作為互相比較治療成果的基礎。 這部分的研究成果，更可以合理化斷指再植的嘗試接合率以及存活率。

挽救受傷的手，不單單只是醫治一位傷患，更救治了一個家庭，重建社會勞動力與生產力。 這是顯微外科醫師的任務與使命，非常具有意義。 這本論文紀錄了我的工作與研究成果，期待這些工作成果，可以幫助未來的外科醫師，成功救治更多複雜的手部外傷。

關鍵詞： 外傷性斷指；指尖再植手術；靜脈淤塞；放血治療；充分清醒局部麻醉；斷指傷害嚴重程度分級

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ABSTRACT

The dexterous hands of human beings have created advanced technology and a highly civilized society, helping us to improve our daily lives. The vast majority of work relies on the hands, especially in the case of poor vision, and often requires hand touch to assist vision and complete various tasks. Therefore, our hands are one of the most frequently injured parts and a common reason for hospital emergency department visits. These accidental injuries to the hands are very urgent, painful, and require immediate treatment. On the other hand, the structures of the hand are delicate and complex, and repairing hand trauma requires superb microsurgical skills, as well as a high degree of care and patience.

Among the hand injuries, traumatic amputation is the most dangerous form. Reviewing the literature, most of the severed finger injuries were not replanted for treatment, thus losing the chance of recovery. Even though patients undergo replantation, the reported survival rates for finger replantation vary widely. The reason for such a large difference is the inherently random and highly unpredictable injury of severed digits, combined with the need for cumbersome microsurgical techniques and labor-intensive post-operative care. The main theme of this dissertation, which contains four core themes, is a step-by-step approach to overcoming vascular problems and simplifying the surgical anesthesia process, to increase the attempted rate and the survival rate in amputated fingers surgery.

The first part is distal digit replantation which the small caliber of vessels makes this surgery very difficult. There are no suitable veins beyond the nail bed, so most surgeons have given up on all attempts to replant it. I treated artery-only replantation in the fingertips,

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and the survival rate of the replant was 81.8%. The result is not inferior to the survival rate of replantation with both arterial and venous anastomosis. However, in the other group, where the artery and vein were not repaired, the survival rate of the fingers was 0 %. Therefore, the distal digit replantation relies on digit artery repair, not venous anastomosis. The results of this part encourage surgeons to try to replant the severed fingertips as much as possible.

Generally speaking, a standard digit replantation involves both arterial and venous anastomosis to rebuild the circulation of severed fingers. Traditionally, venous occlusion occurs after digit replantation, and it is necessary for urgent reoperation, to rebuild the vein once again. Since the replantation of the severed fingertip does not rely on venous anastomosis, I adopted the method of bloodletting to save the venous occlusion. The result of this part shows the trend of bloodletting is better than the effect of reoperation. However, bloodletting has a higher risk of blood loss and requires more blood transfusions. Faced with the sudden occurrence of venous insufficiency after digit replantation, I have established a treatment strategy to help clinicians select suitable patients to receive appropriate treatment. The research results in this part help surgeons to effectively deal with venous occlusion after replantation, avoid unnecessary secondary operations, reduce the burden of postoperative care, and improve the success rate of salvage.

Traditionally, patients receive general anesthesia to facilitate microsurgery of digit replantation. Preparing for general anesthesia, the patient waits for a long time in the emergency department. The third part of this dissertation is to use wide-awake local anesthesia for the digit replantation. The success rate of replantation under wide-awake local anesthesia is 81.25%, which is not inferior to that under general anesthesia. The indications

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for wide-awake local anesthesia include single-digit amputation, absence of severe crush injury, estimated operation time of fewer than 3 hours, and a psychologically stable and cooperative patient with no associated life-threatening injury. This simplified anesthesia process can help surgeons and patients to replant severed fingers more conveniently, and even further increase the willingness and attempt rate of replantation.

The fourth part of this dissertation is to establish a grading score for assessing the injury severity of traumatic digit amputations. Reviewing the literature, it is roughly divided into sharp injuries, crush injuries, or avulsion injuries. However, most traumatically amputated injuries are mixed and vary in severity. I give grades according to the injury severity, and the more serious the damage, the higher the score. A good trauma grading system, which clearly defines the severity of damage to each tissue, can help physicians to assess the injury and scientific records, and serve as a reference basis for comparing treatment outcomes. The results of this part can further rationalize the attempt rate and survival rate of digit replantation.

Saving an injured hand is not only to heal a patient but also to save a family and restore the labor force and productivity of society. This is the responsibility and privilege of microsurgeons. This dissertation records my work and research results, and I hope these results can help future surgeons successfully treat more complex hand injuries.

Keywords: traumatic digit amputation, fingertip replantation, venous congestion, bloodletting therapy, wide-awake local anesthesia, injury severity grading

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Chapter 1: INTRODUCTION

The high level of human civilization initiates from the brains and mostly outputs from the hands. The bilateral human hands locate at the end of the forearms symmetrically. A human hand normally has five digits, including four fingers and one thumb. Each human finger has three phalanges connected by two interphalangeal joints. The opposable thumb has two phalanges and one interphalangeal joint. Surround the skeleton system of the hand are tendons, ligaments, muscles, blood vessels, nerves, and skin envelopes. These delicate structures composed a functional and beautiful hand with dexterity. The hand plays a very important role in our social life.

The human hands, with all digits, help us to explore our living environment and to finish most of our daily work. When direct vision is not available, such as in a dark room or at the corners behind a machine, we usually reach out our hands to accomplish tasks beyond visually. Therefore, our hands are prone to withstand very high risks of various injuries. Hand trauma is a frequently encountered injury in the emergency department of hospitals, causing 6.6–28.6% of accident and emergency visits. (Dębski et al. 2021) The commonly traumatic injuries on the hands are skin lacerations, tendon ruptures, neurovascular disruptions, joint dislocations, or bone fractures. It should note

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that many complicated hand trauma through combinations of these injuries. The more severe the injury, the more difficult it is to be surgically repaired, and the worse hand function will restore. Without proper treatment, the injured hand might endure functional impairment permanently and even consequent tissue loss.

Traumatic amputation is one of the most severe injuries to the hands for sure. The separated part of the hand in the traumatic amputation injury bears an ischemic threat that will result in tissue necrosis if not treated properly and urgently. The digits of the hand define as the terminal organs from the anatomic point of view. The terminal branches of digital nerves and arteries are extremely tiny structures that are not easy to be visualized clearly with our bare eyes. Without a magnification operating microscope, it is impossible for hand surgeons to confidently handle and well repair the terminal blood vessels or nerves of the hands.

Traditionally, there are several reconstructive methods, which do not require an operating microscope, to repair traumatic amputations of the hand. These include bone shortening, skin grafting, local or regional flaps transfer, et cetera. Bone shortening to gain adequate skin and soft tissue coverage in an amputated finger is the easiest way to close the wound. Skin grafting in the amputated stump requires a well-prepared wound

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bed to achieve wound closure. Local or regional flaps might need staged operations to achieve soft tissue coverage on the traumatic digit wound. Although fewer surgical techniques are demanded, all of the aforementioned non-microsurgical reconstructive methods will sacrifice innocent tissue. Furthermore, the functional and aesthetic results of these conventional reconstruction methods are suboptimal for a traumatic hand.

The operating microscope is helpful to repair very tiny structures such as small blood vessels and nerves, which are usually less than 3 mm in diameter. This surgical technique is called microsurgery and is paramount important in saving a traumatically amputated finger. The operating microscope provides adequate illumination and magnification in the surgical field for repairing small structures of our bodies. Meanwhile, specialized instruments and tiny needles with ultrafine sutures also play important roles in microsurgery. The era of modern microvascular surgery began in 1960 with the tremendous work of Jacobson and Suarez. (Jacobson et al. 1962) This microsurgical technique enables us to reattach severed digits or other amputated parts to the body by reconnecting the small blood vessels and reestablishing tissue perfusion. The first successful replantation of an upper arm amputation was performed by Malt and McKhann in 1962. (Malt et al. 1964) The first successful digital replantation, a thumb, was performed in 1968 by Komatsu and Tamai. (Komatsu et al. 1968)

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The human fingers compose several unique and delicate structures such as fingernails, glabrous skin, fingerprints, finger pulp, and phalanges. Without the severed part, it is not easy to reconstruct a natural-looking finger after the amputation injury. Although there are many reconstruction options for finger amputation, replantation is always the first attempt, especially in Asia, when the amputated part is available and suitable for replantation surgery. The microsurgical technique offers an opportunity for replantation to rescue traumatic amputation injury without sacrificing innocent tissue. A successful digit replantation restores the best outcome of the traumatic hand functionally and aesthetically.

Replantation is a very complicated surgical procedure and requires prolonged operative time. Usually, replantation surgery is conducted under general anesthesia to achieve full paralysis for this prolonged and delicate process. The sequence of surgical procedures for digit replantation consists of bone or joint fixation, extensor and flexor tendons repair, digital arteries anastomosis, digital nerves coaptation, digital veins reconnection, and skin envelope closure finally. Every step of the digit replantation requires the restoration of each anatomic structure precisely. A good bony alignment and skeleton fixation provide stable structure and facilitate subsequent tendon repair.

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Accurate tendon repair ensures motion recovery after the replanted digit survival. The survival of the replanted part relies on satisfactory arterial reconstruction and venous drainage to restore adequate tissue perfusion. This portion of microvascular surgery for digit replantation is highly surgical skill demand. There is no leeway to make any mistakes; otherwise, the replant may not survive. Skin closure without undue tension is the final step of digit replantation. Any excessive suture on the skin closure will compromise blood circulation, which leads to replantation failure.

Since digit replantations are complicated surgical procedures, that time consuming and have a monetary cost, the decision to undergo attempt replantation should be precautious and thoroughgoing. Deciding to attempt replantation of a severed digit is often extremely difficult. Many factors influence the decision-making on the replantation or not and must take into consideration patient-specific, injury-specific, and hospital system/care-team factors. Patient-specific variables include age, the presence of other medical or surgical conditions, and one's motivation to undergo a difficult procedure, followed by a lengthy recovery. Injury-specific variables include mechanism and extent of injury, injury type, zone or level of it, injured hand, the method of preserving the amputated digit, and importance of the part. Hospital system/care-team factors include the availability of anesthesia and surgical facilities, the start time of

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surgery performed, the expertise of the surgeons, and the adequacy of the recompensation. To replant or not to replant, that is the question. Deciding on replantation versus not replantation on the spur of the moment is not always easy. One has to weigh the request and expectations of the patient with the short-term and long-term prognosis of the replanted part.

Reviews show that digital replantation attempt rates in the United States range from only 7% to 27%. (Shale et al. 2013) The average attempt rates for digital replantations were 38.9% to 25.3% in Taiwan. (Chang et al. 2015) A 2007 survey of members of the American Society for Surgery of the Hand found that 44 percent of their members opt not to perform microsurgical procedures. (Payatakes et al. 2007) They cited busy elective schedules (51 percent), low microsurgical confidence (39 percent), and inadequate compensation (25 percent) as their primary motives for avoiding replantation surgery. Consequently, the wide variability of survival rates from 33% to 97% in the cited literature demonstrates the complexity of the operative indications and the technically demanding nature of the replantation operation itself. (Cho et al. 2018; Billington et al. 2021) As surgeons continued to push the boundaries of microsurgery, novel techniques were proposed to manage the difficulties of salvaging amputated digits. This dissertation aims to find out the factors that influence digital replantation attempt

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rates, overcome the difficulties during digit replantation, and increase the survival rates of digit replantations. There are four parts of this work regarding the following:

(1) Distal digit replantation where vascular accessibility is very difficult

(2) Treatment strategy for venous congestion after digit replantations

(3) Minimize medical demand by digit replantation under wide-awake local anesthesia

(4) Injury severity grading system for digit amputations

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The distal digit, in terms of a fingertip, can be defined as the structures beyond the level of the distal interphalangeal joint. It includes the nail plate, nail matrix, distal phalanx bone, pulp tissue, tiny vessels, branched nerves, and glabrous skin with fingerprints. The fingertip locates even more distally and, hence, is more vulnerable to being injured. Fingertip amputation injury is not uncommon in the emergency department. The distal digit has specialized structures and functions; therefore, its restoration and reconstruction after an amputation injury are special issues. (Sebastin et al. 2011) The concept of fingertip replantation is different from finger replantation by the fundamentally anatomic structures. In other words, distal digit replantation remains more challenging because of the small size of blood vessels and even the inaccessibility of sizable vessels for microvascular anastomosis. (Kim et al. 2013) The first part of this dissertation is to review the author's clinical experience with distal digital replantation and to test the hypothesis that success in distal digit replantation is not dependent on the venous anastomosis.

Based on the first part of this work, the distal digit amputation could be replanted successfully even without venous anastomosis. However, the replant might experience a short period of venous congestion after the replantation surgery. In 1989, Barnett et al first used instead of the difficult venous anastomosis procedure a chemical leech in

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fingers replantation. (Barnett et al. 1989) He reported three artery-only replanted digits, which survived with a 9-day intrareplant subcutaneous heparin injection. This shows that an intrareplant subcutaneous heparin injection with an external bleeding wound, which is also termed chemical leech therapy, becomes a treatment option for venous decompression when vein anastomosis is not feasible in digit replantation. The second part of this dissertation reviews our experience in applying chemical leech therapy for external bloodletting as a rescue procedure, compared with surgically venous re-anastomosis in cases of venous compromised digit replantation. It is hypothesized that a chemical leech therapy with controlled external bloodletting may be a good alternative treatment for venous congestion of the digit after a standard replantation consisting of at least one artery and one vein reconstruction.

The digit replantation requires extremely skillful microsurgical techniques and is performed under general anesthesia or brachial plexus block by default. In 2011, Donald H. Lalonde published an article on wide-awake hand surgery without sedation medication. (Lalonde DH. 2011) In his concept, wide-awake local anesthesia (WALA) hand surgery means no sedation, no tourniquet, and no general anesthesia for hand surgery. The only medication the patients received is a combination of 1% lidocaine with 1:100,000 epinephrine. He claims the advantage of not sedating the patients to

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maintain the ability of the patients to perform active hand movement during and immediately after the hand surgery. Meanwhile, epinephrine deletes the need for an arm tourniquet. Today, the wide-awake local anesthesia no tourniquet method is widely accepted in hand surgery, except for finger replantation surgery. To extend the concept of wide-awake local anesthesia in hand surgery, as the more maturation of microsurgical skills, the third part of this dissertation is to share my clinical experience in finger replantation under wide-awake local anesthesia without sedation and without epinephrine medications. It is hypothesized that digit replantation under wide awake local anesthesia is feasible and is not inferior to under general anesthesia in certain indications.

Microvascular surgery enables replantation to be a treatment choice for traumatic amputation of digits. In treating amputated injury of the hand, the surgeon has to make clear that the amputated part and the patient are both in satisfactory condition for the replantation. Some surgeons proposed relative indications and relative contraindications for digit replantations. (Pederson WC. 2001) Traditionally, the injury severity of digit amputation is classified as clear-cut, crush, or avulsion injury. (Soucacos PN. 2001) Severely crushed or avulsed digits of the amputation might be considered infeasible for replantation. But here raise the questions of how crush is severe crush and how avulsion

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is severe avulsion. In a clinical scenario, the crushed amputated digit is usually companies with some degree of avulsion injury, and vice versa. Few works from literature focused on the injury severity of the amputated part and stump of the hand. Lacking a practical grading system, we are unable to scientifically evaluate the injury severity of amputations preoperatively and treatment outcomes postoperatively. The final part of this dissertation is to focus on the trauma severity of the regional tissue and to propose a grading system for the digit amputation injury of the hands. Since most traumatic amputation has mixed crush and avulsion injury, I take this into general consideration. The assessment of each module of the amputation can conduct in the emergency room. It provides physicians a systemic evaluation of the amputation injury and better communication preoperatively.

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Chapter 2: MATERIALS AND METHODS

2.1 Distal digit replantation

The first part of my work was a retrospective study. Between January 2009 and August 2012, twenty-eight consecutive patients with 31 complete distal digital amputations at or distal to the distal interphalangeal joint of the finger or at the interphalangeal joint or distal phalanx of the thumb were included in the study. Data regarding patient demographics, causes of injury, replantation techniques, surgical outcomes, and functional and cosmetic outcomes were collected and analyzed. Fisher's exact test was used for statistical analysis. The indications for replantation by performing vascular anastomosis were as follows:

1. Availability of the amputated part.
2. Absence of severe crush injuries in the amputated part or stump.
3. Presence of healthy arteries or veins under microscopic exploration.
4. Psychologically stable condition without life-threatening injuries.

All finger replantation procedures were performed by the same surgeon with qualified surgical skills in the operation theaters. The injured digits and the amputated parts were examined under the operating microscope to assess the severity of the injury

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and the feasibility of replantation. Once microvascular replantation was considered feasible, the surgical procedures began with bone fixation, followed by trtery and vein anastomosis after adequate débridement and cleansing. If the amputated part had no sizable artery, it was reattached to the injured stump and treated as composite grafting. If the digital vein was not available, artery-only replantation was performed. To prevent venous congestion, nail-plate removal and nail-bed periodic abrasion were performed prophylactically only in replantations without venous anastomosis. Topical administration of heparinized saline (25,000 units of heparin in 500 ml of saline solution per day) was performed repeatedly for 7 days. Medicinal leeches were not used, as they are not available in my hospital. Because of the very tiny structures in the amputated distal digits, I did not use any vascular graft to repair digital arteries or veins in this series.

According to the reconstruction method, the amputated digits were divided into three groups: group A was replanted with both digital arterial inflow and venous outflow reconstructions; group B was replanted only with arterial inflow reconstruction; and, group C was reconstructed as composite grafting (no vascular reconnection). The survival outcome was measured on the seventh day after replantation by visual assessment and was defined as returning circulation to the fingertip with normal skin

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color and pulp fullness. The patients were followed for at least 2 months. Fisher's exact test was used for statistical analysis.

2.2 Venous congestion treatment

The second part of my work was reviewing the treatments for venous congestion of the replant after a standard replantation surgery consisting of at least one artery and one vein reconstruction. It was conducted by retrospectively reviewing medical records and approved by the institutional review board (IRB No. 201904012RINA). There were 131 amputated digits that underwent standard replantation surgery between January 2013 and December 2019. The aforementioned replantation surgeries were performed by the same surgeon with uniformly surgical techniques. Postoperatively, these patients received standard medical care of oral aspirin (100 mg/day) and intravenous heparin (2,500 units/ three times a day) during 7-day hospitalization. We excluded patients younger than 18 years old from this study. Among the 131 replanted digits, 22 documented diagnoses of venous congestion and received immediate treatment were collected for this study. The patients underwent either emergency surgical venous re-anastomosis in the operation theater or external bloodletting therapy at the bedside. The type of treatment was determined by the patient's gastric preparation, the patient's willingness, and the clinical medical situation: the availability of the operating room,

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surgical facilities, the surgeon, and the anesthesiologist.

The primary outcome of this part study focused on the replantation survival rate in the one-month postoperative follow-up. Patients' characteristics, digit injury levels, operation time, onset timing of venous congestion, and the amount of blood transfusion were also taken into account in our analysis of treatments' efficacy.

External bloodletting procedures

External bloodletting therapy can be conducted at the bedside when venous congestion is noticed clinically after finger replantation. First, we use a No.11 blade to create a slim wedge-shaped stabbing wound at the tip of the replanted digit. Then, intrareplant subcutaneous heparin injections are administered periodically into the stabbed wound with 500 IU heparin via a 25-gauge needle. Blood would ooze out from the wound, initially dark deoxygenated blood, followed by fresh oxygenated blood in a few minutes **(Figure 1)**. Intrareplant subcutaneous heparin injections are usually once to twice daily until neovascularization has established a working venous network around the sixth postoperative day. Decisions regarding treatment initiation and cessation are based on the clinical judgment of the medical staff. After weaning the heparin injection,

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the bleeding will cease gradually, and the stabbed wound will heal with an inconspicuous scar.

2.3 Digit replantation under wide-awake local anesthesia

With the improvement in surgical instruments and microsurgical skills, the third part of my work was moving forward by conducting digit replantations under wide-awake local anesthesia (WALA). Patients who received digit replantation under wide-awake local anesthesia from January 2013 to October 2019 were included in this part of the retrospective study. Demographic data included surgical outcome, operative time, patient tolerance, and length of the hospital stay. Indications for finger replantation under wide-awake local anesthesia were defined as follows:

1. Sharp finger amputation injury
2. Estimated operation time less than three hours
3. Mentally stable and cooperative patients

Procedure for Wide-Awake Local Anesthesia

Using a 27-gauge needle, 1% or 2% lidocaine without epinephrine was injected subcutaneously at the midpoint of the volar crease at the level of the metacarpophalangeal joint. If necessary, an additional dose of lidocaine was given later.

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This technique was described in the literature as wide-awake local anesthesia and could be used for finger surgery.

Surgical Procedures for Digit Replantation

The amputated digit and the injured stump were examined under a surgical microscope to assess injury severity. At the beginning of the operation, a digit tourniquet was placed around the base of the affected finger near the level of the metacarpophalangeal joint. The digital arteries were identified and temporarily controlled by microvascular clips. Immediately afterward, the digit tourniquet was released. Replantation began with bone or joint fixation, tendons repair, digital vessel anastomoses, digital nerves readaptation, and, finally, skin closure in sequential order. Vein graft interposition was needed if there was an insufficient length in vascular reconstruction. In case of an unavailable vein, as in Ishikawa's subzone I to subzone III amputation, the nail was removed or chemical leech therapy was used instead of venous reconstruction. Postoperative care focused on maintaining adequate replanted tissue perfusion until the establishment of stable microcirculation. The patients were dismissed after postoperative days 7 to 8. Standard rehabilitation programs are followed after complete wound healing. The surgical results of replantation under wide-awake local anesthesia were compared with those under general anesthesia.

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2.4 Injury severity grading system

Based on 20 years of experience treating hand trauma, I deduce a systemic evaluation for the severity of an amputated thumb or finger. The eight modules, which might require repair in a replantation operation, include the bone, joint, extensor tendon, flexor tendon, artery, nerve, vein, and skin. By X-ray examinations and clinical assessment of each component, physicians assign a score for each structure according to its injury severity. In general, the bigger the number assigned to each item means more severe the traumatic injury of the tissue and requires the more advanced surgical technique to repair it.

To make a clear description, complete amputation of a digit defines as a complete separation of the part from the body with no bridging tissue. In other words, a severe trauma hand with any connected tissue between the injured digit and the body refers to an incomplete amputation. Total amputation of a finger means the injury level is at the metacarpophalangeal joint or the base of the proximal phalanx. When the amputation level is at or distal to the proximal interphalangeal joint with a remnant stump; namely, this injury is a subtotal amputation.

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Chapter 3: RESULTS

3.1 Survival rates of the distal digit replantation

There were 28 consecutive patients with 31 amputated digits included in this part of the present study. The male-to-female ratio was 4:1. The mean age of the patients was 42.7 years (range, 5 to 68 years). Of the 31 digital injuries, 13 were cutting wounds, and 18 were crush injuries. Amputations at or distal to the distal interphalangeal joint of the finger were observed in 24 cases, whereas seven digits had injuries at the interphalangeal joint or the distal phalanx of the thumb. All finger replantation procedures were performed by a single surgeon with uniformly surgical quality. General anesthesia for replantation was administered to 26 patients, whereas local anesthesia was administered to two patients.

The amputated digits were divided into three groups: group A included 16 digits replanted with both digital arterial inflow and venous outflow reconstructions, group B included 11 digits replanted only with arterial inflow reconstruction, and group C included four digits reconstructed with composite grafts. The success rate in group A was 81.3 percent (13 of 16), whereas that in group B was 81.8 percent (nine of 11). None of the composite grafts used in group C survived **(Table 1)**. Group C had the

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lowest survival rate ($p < 0.05$); however, the difference in the survival rate between group A and group B ($p > 0.05$) was not significant. As some data on the Tamai classification were missing, it was difficult to correlate the outcomes with Tamai zones.

The average follow-up was three months (range, from two to nine months). Data showed that 90 percent of the pulp volume was restored, nail deformity was noted in all digits that were replanted without venous anastomosis, and nerve repair was not performed; however, the adequate protective sensation was restored in all replanted digits. In addition, neuroma formation and cold intolerance were absent. Two-point discrimination was measured in one replanted digit with venous anastomosis and two without; the average value was 7.5 mm. Cold ischemia time was estimated in six cases, and the mean value was 3.5 hours. Using power and sample size calculation, the power of the study is 0.05.

3.2 Comparison results of venous congestion treatment

From January 2013 to December 2020, 108 patients with 131 traumatically amputated digits all underwent replantation by the same senior surgeon. Of those digits, 22 encountered venous congestion and required emergency treatments during the postoperative hospitalization, 16 males and six females. They suffered from traumatic

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amputation at varying injury levels and received at least one arterial and one venous reconstruction in the primal replantation. The patients' ages ranged from 22 to 87 years (mean=43.9, SD=16.58 years). Venous congestion occurred clinically at 8 to 62 hours (mean=28.1, SD=17.43 hours) after the replantation surgery.

According to the treatment modality of venous congestion, these 22 patients were divided into two groups. Group A contains nine digits treated with returning to the operation theater and venous reconstruction once more. The waiting time for the surgically venous revision ranged from 102 to 228 minutes (mean=165.56, SD=41.47 mins). The re-operation time ranged from 125 to 245 minutes (mean=179.22, SD=40.74 mins). During or after the surgical procedure, four patients received a blood transfusion with two units of packed red blood cells. Four of nine (44.4%) replanted digits survived in group A (**Table 2**). Group B contains 13 digits treated with external bloodletting at the bedside to relieve venous congestion. Each treatment lasted for 4 to 7 days (mean=5.92, SD=0.86 days). Eight patients in this group received a blood transfusion with packed red blood cells, ranging from 2 to 6 units during the postoperative hospitalization. Eleven of thirteen (84.6%) replanted digits survived in group B (**Table 3**). Between group A and group B, the comparisons of the patients' ages, the primal

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replantation time, and the onset timing of venous congestion are no statistical differences (**Table 4**). The mean blood transfusion amount in group B is greater than group A, although it is not statistically significant.

The case one in group A is a 29-year-old woman who suffered from traumatic amputation over the left ring and small fingers at the proximal interphalangeal joint level. She was sent to our emergency department and underwent the two-finger replantation urgently. During the hospitalization, her left ring finger turned blue-purple unexpectedly 22 hours after the replantation surgery. Meanwhile, the circulation of her left small finger was normal. Under venous insufficiency, she was taken back to the operation room to revise venous re-anastomosis of the ring finger. 245 minutes were spent rebuilding the venous flow of the ring finger with a segment of vein graft, and two units of packed red blood cells were used for transfusion. However, the circulation of her left ring finger did not maintain on the third day postoperatively. Making the situation even worse, her left small finger, which was not enrolled in this study, became hypoperfused after the revision operation. Eventually, neither her left ring nor small fingers survived.

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I developed a standard treatment algorithm for managing congested digits in 2020. Hereafter, eight patients encountered venous congestion in the replanted digits, and they were treated following the flowchart **(Figure 2)**. Among them, seven patients merely received bloodletting therapy, and one patient received once more venous reconstruction surgically after executing bloodletting. All of the replants survived, and the wounds recovered smoothly. **Table 5** summarizes the results of these patients. This treatment flowchart helps our medical staff select the suitable patient to return to surgery meanwhile avoid unnecessary surgical risks for the rest of the patients.

3.3 Survival rates of wide-awake local anesthesia replantation

Moving the digit replantation forward, I simplified surgical anesthesia to make replantation more convenient. Fifty-one consecutive patients who received single-digit replantation were enrolled in this study and sorted into two groups according to the anesthetic method. Neither the male to female ratio nor the mean age differed significantly between the two groups **(Table 6)**. All replantations were performed by the same microsurgeon with uniformly surgical skills. Between January of 2013 and October of 2019, 16 (treatment group) of the 51 patients received single-finger replantation under wide-awake local anesthesia treatment **(Table 7)**. Thirty-five patients (control group) received single-finger replantation under general anesthesia treatment

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(Table 8). The data did not show any significant difference regarding the injury level between the two groups. The overall waiting time differed from 96 to 432 minutes, with a mean waiting time of 191 minutes. The waiting time was significantly shorter in the wide-awake local anesthesia group (165.44 versus 202.69; $p = 0.05$) **(Table 6** and **Figure 3**). The duration of all replantation surgeries differed between 55 and 449 minutes, with a mean surgical time of 207 minutes. The operation time was significantly lower in the wide-awake local anesthesia group (142.81 versus 235.71; $p < 0.05$) **(Table 6** and **Figure 4)**. All patients who underwent wide-awake local anesthesia cooperated well during the operation. Therefore, no intraoperative changes from the wide-awake local anesthesia to the general anesthesia were necessary. The demographic data of all the patients are summarized in Tables 6 through 8.

After replantation surgery, all of the patients were hospitalized for postoperative care. In cases of unavailable venous reconstruction, the patients required intrareplant heparin injection as chemical leech therapy for 7 days. The color and temperature of the replanted digit were monitored closely to ensure adequate perfusion. There was no significant difference concerning the length of the hospital stay between the two groups **(Table 6** and **Figure 5)**. The mean hospital stay overall was 7.61 days. The wide-awake local anesthesia group showed a higher replant survival rate (81.25 percent) compared

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to the general anesthesia group (74.29 percent). However, the difference was not statistically significant ($p = 0.73$). The overall replantation survival rate was 76.47 percent.

3.4 Injury severity grading system

Traumatic amputation of fingers or the thumb is a random injury, which leads to various degrees of tissue damage. I worked on this kind of injury for 20 years and deduced a grading system to evaluate their severity. **Table 9** displays the grading score for each structure in a finger or thumb amputation injury. A clear-cut amputation of a digit has lesser tissue injury, as shown in **Figure 6**. **Figure 7** illustrates different grade injuries of the skeleton in a digit amputation. Regarding the tendon, **Figure 8** demonstrates the extensor and flexor injuries from grade two to grade four of digit amputation. **Figure 9** displays grade two to grade four injuries for the digit artery and nerve. The amputation injuries of the vein and skin envelop from grade two to grade four, illustrated in **Figure 10**. This grading system applies to a finger or thumb amputation; however, the surgeon should individually evaluate each digit in multiple digits amputation injury.

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Chapter 4: DISCUSSION

4.1 Distal digit replantation with or without venous repair

Although microsurgical replantation is the treatment of choice for digital amputations, it is not popular in centers in which the technique is not available or not widely accepted by surgeons who prefer traditional surgical approaches. In the present study, I report my clinical experience with distal digital replantation performed by a single surgeon with more than 10 years of microsurgery experience, with a special focus on replantation without venous anastomosis. In this series, the overall success rate for distal digital replantation was 81 percent. This was comparable to the results of previous studies reported in the literature, in which the success rate varied from 70 to 90 percent. In 2011, Sebastin systemically reviewed the outcomes of replantation of distal digital amputations and observed that the outcome of distal digital replantation depended mainly on the survival of grafts. (Sebastin et al. 2011) In general, the factors affecting the survival of distal digital replantation include the vessel size, vein availability, technical skills of the surgeon, ischemia time, and the severity of the soft-tissue injury. The vessels in the distal digit are small; therefore, replantation requires a high level of surgical skill. The diameter of the vessels is less than 1 mm, and 11-0 nylon sutures are often required for vascular anastomosis. Improper suturing may lead to vascular

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thrombosis, which can eventually cause replantation failure.

This part of my study did not reveal any difference in the success rate between distal digit replantation with and without venous anastomosis. As veins are not always available for anastomosis in distal digit replantation, artery-only replantation has no choice but becomes a common surgical procedure. Venous congestion is an important problem, as it may lead to replantation failure. However, several strategies are available to overcome venous congestion in the replanted digit, including external bleeding by removing the nail plate, creating a stab wound in the amputated part, arteriovenous shunting, and performing the subdermal pocket procedure. None of these methods except nail-plate removal has been used to treat our patients in this part of work. Artificially induced stab wounds with subcutaneous injection of heparin can improve venous drainage in the amputated part; however, this method is associated with a risk of infection and substantial blood loss. The arteriovenous shunt has been used to reestablish the venous system by joining the artery in the amputated part with a vein in the stump. However, the procedure is time-consuming and not always possible because of the frequent lack of vessels. Finally, the subdermal pocket procedure is not popular among surgeons, as it is a two-stage operation. The main drawbacks of the nail-plate removal method are blood loss and the risk of wound infection.

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Some may argue that fingertip replantation may not be necessary for distal digital amputation, as the function of the hand may be minimally affected, especially in single-digit injuries except for those of the thumb. In some centers, traditional surgical treatments such as bone shortening, primary closure, and the use of local or distant flaps are preferable. Long-term studies comparing the advantages and disadvantages of various reconstruction methods, such as the study performed by Sebastin, are limited; however, traditional surgical treatments compromise the digital structure and function for wound closure. (Sebastin et al. 2011) Pedicled flaps such as thenar or abdominal flaps are commonly used. However, in addition to flap bulkiness and donor-site morbidity, these techniques require a staged operation, which is one of the main drawbacks of these surgical procedures. In contrast, the main benefits of digital replantation are the preservation of digital length and function. Furthermore, a nearly normal appearance of the hand can be achieved in most patients.

In this series of my work, 12 percent of the amputated digits received composite grafts, although none of them survived. Despite the small number of cases included, my results confirmed that the success rate of composite grafting is low in adult patients and probably also in the part amputated as a result of crush injuries. The possible causes of

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failure include severe soft-tissue injuries and bulkiness of the tissue mass, which may lead to an inadequate supply of oxygen and nutrition. Theoretically, the repair of sharp amputations should be associated with a higher success rate than that of crush injuries. However, no related data were available in this part of the retrospective study. In addition, assessing the effect of the mechanism of injury on the success rate was often difficult because the injuries were frequently of the mixed type and included sharp injuries associated with crush injuries. These explained why this part did not present success rates for amputations that were considered a crushing mechanism versus a sharp injury. Although severe crush injury has been mentioned as the major cause of failure in replantation surgery, an objective tool for measuring the severity of crush injuries is not available. Further research aimed at developing a system to assess the severity of soft tissue injuries may be beneficial. That will be my future work for part 4 of this dissertation.

Data regarding the functional and aesthetic outcomes of the replanted digit were limited in this part of the retrospective study. Moreover, the long-term follow-up was inadequate; only three of 13 successfully replanted fingers in group A were followed for more than 5 months and only two of nine successful cases in group B were followed for more than 7 months. We showed that 90 percent of the pulp volume was restored in

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cases with regular follow-up. However, we were unable to observe an association between pulp atrophy and venous anastomosis. Nail deformity in replanted digits without venous anastomosis was attributed to repeated nail-bed abrasions in artery-only replantation. Although nerve repair was not performed in the replanted digits, the adequate protective sensation was restored. This was comparable to the results obtained by Sebastin, who reviewed the surgical results of digital tip replantation and concluded that nerve repair was not essential in distal digital replantation because the protective sensation was restored regardless of the nerve repair status. (Sebastin et al. 2011) In this part of my series, there was no significant difference in the functional sensation between replantations, as none of the patients complained of poor sensation, neuroma, or cold intolerance after a period of follow-up. Although measurements of distal interphalangeal and proximal interphalangeal joint range of motion were lacking in the series, joint stiffness was seldom a complaint. This can be explained by the fact that the level of amputation in these patients was mainly in Tamai zone I, which is distal to the insertion of the flexor digitorum profundus tendon.

The main limitation of this part of the study is its retrospective nature. Data regarding ischemia time, the severity of soft-tissue injuries, sensory recovery, functional and cosmetic outcomes of the replanted digits, and smoking status of the patients were

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not properly and completely documented, leading to weakness in data collection and interpretation in this part of the study. Statistically, the power of the study is 0.05, which is considered low and is probably attributable to the small sample size.

4.2 Venous congestion surgical or non-surgical treatment

Microsurgical techniques are crucial in finger replantation. A highly skilled and experienced surgeon is required to accomplish this complicated surgery. The protracted operation time, concentration throughout the whole procedure, and cumbersome postoperative care make finger replantation extraordinarily challenging for hand surgeons. Although the success rate of replantation has improved in recent years, replantation failure still exists. Effective monitoring of the replanted digit plays an important role in the timely treatment of circulation insufficiency. Several monitoring methods have been reported, such as the capillary refilling signs, skin color, turgor, audibility of arterial Doppler tones, and amplitude of pulp pressure tracing. (Yu et al. 2015) Nevertheless, the above methods are observer-dependent and interfered with by wound dressing, which might cause potential harmful consequences in perfusion disturbance.

Vascular thrombosis is the most feared complication of replantation and occurs

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mostly in the vein because of its relatively low flow state. After digit replantation, the reported incidence of venous insufficiency ranges from 7 to 32 percent. (Iglesias et al. 1999) Postoperative venous congestion in a replanted digit can be identified clinically by the dusky purple appearance of the skin, brisk capillary refill, and dark-colored blood after pinprick. It is more rapidly lethal to the replant than arterial due to the progressive accumulation of toxins and thus requires emergency treatment. (Angel et al. 1990) Therefore, venous insufficiency would lead to irreversible tissue damage if not treated timely and effectively. The literature provided details of salvage operations for rescuing venous congestion after ear reconstruction. (Facchin et al. 2018) In 2011, Zhao reported 10 cases of replanted digits with venous congestion rescued by cross-finger flaps. (Zhao et al. 2011) Lee PK et al. reported 29 replanted digits, which underwent the pocket method as a replacement for venous anastomosis. (Lee et al. 1999) By the standard of microvascular reconstruction surgery, it requires emergency surgical exploration of the compromised vein and reconstruction of venous drainage again to reverse venous congestion before the replant necrosis. However, emergency rescue operations require an immediate return to the operation room and pose higher anesthetic or surgical risks for the patients. Surgical intervention for thrombosis generally involves anastomotic revision or interposition vein grafting, but the occurrence of re-intervention failure is common. (Hidalgo et al. 1998; Ichinose et al. 2003) Having poor vascular or soft tissue

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quality as the cause for venous failure after the primal replantation often leads to venous failure again in the following surgical re-exploration, especially during the postoperative inflammation phase of the healing process.

Leech therapy had been implemented for medical purposes for many centuries, and it became popular again in the 1960s because of the success demonstrated by plastic and reconstructive surgeons in treating tissue compromise from venous congestion. (West et al. 1991) When medical leeches are unavailable, surgeons apply topical heparin in the iatrogenic wound at the distal pole of the targeted tissue to keep external bloodletting. This procedure mimics the therapeutic effects of *Hirudo medicinalis* and earned the name of chemical leech therapy. At first, Barnett et al used chemical leech therapy in fingertips replantation if sizable veins are unavailable for anastomosis. (Barnett et al. 1989) Afterward, several reports revealed positive results of chemical leech therapy in venous insufficiency replantations. (Iglesias et al. 1999; Toshiya et al. 2007; Justus et al. 2010) From this point forward, it is interesting for me to conduct research on reviewing the efficiency of external bloodletting therapy and surgically venous re-anastomosis for venous compromised digit replantations.

In this part of reviewing, case 1 in group A and case 12 in group B especially

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impacted me. Both cases underwent two-finger primal replantation while only one finger encountered venous congestion. Case 1 was taken back to the operation theater to rebuild venous flow with a vascular graft. This surgery posed a risk to the other replanted finger, and eventually, both replanted fingers failed. Case 12 received external bloodletting therapy on the congested finger at the bedside, and no adverse effect happened on the other replanted finger during the treatment course. Finally, the two replanted fingers of the case 12 both survived. That might imply the risk of early surgical re-exploration is much higher than the risk of blood loss from external bloodletting therapy. Some experienced surgeons believe that the initial surgery should be the “best” that can be done, and rarely return to surgery to attempt secondary repair of the thrombosed vessels. (Pederson WC. 2001) Experience has shown that an early return to the operating room with blood pressure shifts from anesthesia and temperature change can lead to irreversible vascular spasms. (Pederson WC. 2001) Furthermore, if the occlusion occurs later than 48 hours after replant, exploration will disrupt any vital new capillary connections that may have bridged the wound, and the decision to revise in this situation is risky. (Morrison et al. 2007)

On the other hand, non-surgical management for congested replants by external bloodletting therapy might face another risk. If there is total obstruction of venous

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outflow, near-continuous leeching will be necessary for at least 5 to 6 days, and the patient may suffer significant blood loss in the 2 to 6 unit range. (Pederson WC. 2001) Careful monitoring of wound ooze and the patient's hemoglobin are therefore essential. My study also disclosed a mean of 2.15 units of pRBC (SD=2.08 units) transfusion required in group B versus 0.89 units of pRBC (SD=1.05 units) in group A. In contrast with surgically venous re-anastomosis for treating venous congestion, external bloodletting offers another advantage to close monitoring the status of reconstructed arteries in the replant by the amount of bleeding and the color of the blood. The bleeding of abundant bright red blood communicates that the replanted finger is well perfused by the reconstructed arteries. On the contrary, scanty bleeding with dark blood or cease of bleeding signals alarming arterial problems that disturb tissue perfusion. Close monitoring through external bloodletting provides very practical information to differentiate between arterial problems and venous problems. This viewpoint further illustrates the importance of arterial anastomosis in digit replantation. The only two replantation failures in group B of this study were attributed to arterial obstruction fundamentally.

The onset time of venous congestion occurs unpredictably between 8 to 62 hours after the primary replantation in this part of the study, and I did not find a correlation

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with the number of digital veins reconstructed. The average waiting time of surgical preparation for returning to the operation theater is 165.56 minutes in group A, which will certainly delay the treatment of the congested replant and decrease the survival possibility. It is not so efficient to surgically once more reconstruct the digit venous drainage in this situation. From my point of view, postoperative venous insufficiency correlates with the quality of the reconstructed veins in the replanted digits as well as the quality of their soft tissue envelope suffered from traumatic amputation injuries. That accounts for the relatively low survival rate (44.4%), even surgical reconstruction of the digital vein again with a segment of vein graft in group A (six out of nine patients). On the other hand, the replanted digits in group B underwent external bloodletting therapy, which was unrelated to the quality of digital veins, and it showed a trend of higher survival rates. It is worthy to mention that the survival rate in group B is 84.6%, which is similar to my previous report of artery-only digit replantation in the first part of this dissertation. In other words, the survival of digit replantation is not dependent on venous anastomosis but rather on arterial reconstruction. Although external bloodletting therapy could remedy the vein-related failure, no replanted digit is viable in the absence of a satisfactory arterial anastomosis. (Toshiya et al. 2007)

Undoubtedly, good venous reconstruction is one of the important steps to attaining

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survival of finger replantation. It may avoid the blood loss from external bleeding and the burden of intensive nursing care in salvage procedures. (Woo et al. 2015) The decision to take a patient back to surgery for salvage is always not easy for the surgeon and the patient. Since 2020, I developed our strategy for managing venous-compromised digits during the critical postoperative care period. The flowchart **(Figure. 2)** helps medical caregivers to decide between returning surgery or not by three consideration domains. First of all, the availability of the surgeon and the team is a major concern. The surgeon of the primal replantation surgery is responsible for the replanted finger and the function result of the hand. He thoroughly understands the tissue quality of the amputated part and stump. Therefore, he is also the key person to consider the suitability of the replanted digit for returning to revision surgery. From our experience, for example, multiple-digit replantation might be admitted too risky to return to the operation room. The third domain of consideration is the readiness of the patient physically and psychologically. The patient should play a role in deciding on revision surgery. After establishing this flowchart in 2020, I treated eight congested replanted digits with good results. I executed external bloodletting therapy more aggressively, reduced the period of venous congestion, minimized the surgical risks, and increased the survival possibility of the replant. This algorithm enables the caregivers to treat congested digits more efficiently and effectively.

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The last issue of conducting external bloodletting therapy is when to stop it. The reported duration for bloodletting in the replanted digit widely ranges from 3 days to 18 days. (Barnett et al. 1989; Iglesias et al. 1999) The treated replant is dangerous until establishing neovascularization as a working venous network, which is a part of the wound healing process. From my experience, a postoperative 6-day healing process is the minimal requirement in healthy tissue and the medical staff should be alert to the recurrence of venous congestion signs of the replant after stopping treatment. Theoretically, the larger the volume of the replanted digit, it requires the longer the treatment period to achieve a functional venous drainage network and bear more blood loss. In cases of the large volume amputated digit, the veins are prone to be reliable to surgical reconstruction. The surgeon should consider taking the patient back to repair digit veins again surgically in this condition.

This study has several limitations that warrant statements. I conducted this research by a retrospective review of cases of venous congestion after digit replantation. At first, the assignment of treatment in group A and group B is not random. The treatments were determined by the medical staff, based on the clinical situations and availability of facilities at the occurrence of venous congestion. As the patients' ages, levels of injury,

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and trauma mechanisms varied, the number of reconstructed vessels also not equalized during the primal replantation. Although the backgrounds of group A and B are not statistically different **(Table 4)**, it is not easy to conduct a randomized clinical study due to the unpredictable nature of the amputation injury and venous problems in the replants. This part of the sample size is relatively small because all the enrolled cases were replanted by a single surgeon with a reasonable venous compromised rate of 16.8% (22 congested digits out of 131 replantations). In such highly skill-dependent surgery, having all replantations performed by the same surgeon minimized confounding factors in surgical techniques. It showed the trend of blood transfusion and survival rate, but did not establish statistical significance in the difference between the two groups due to the small sample size.

4.3 Wide-awake local anesthesia replantation

The replantation of a single finger other than the thumb has been a debatable issue concerning its benefits and costs. In addition to operative risk and medical expenses, some might argue that single-finger replantation is not necessary, as the function of the hand will only be affected marginally. (Morrison et al. 1977; Weiland et al. 1977) However, for mostly cultural reasons in Asia, amputated fingertips are always under consideration for replantation if possible. To decrease the operative risk in general

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anesthesia and to increase the cost-effectiveness, I recently performed 16 single-digit replantations under wide-awake local anesthesia.

Finger replantations are usually performed under general anesthesia in my institution. The advantages of general anesthesia are anxiety relief and complete paralysis during the operation. This is helpful for the surgeon to perform the microsurgical reconstruction of the vessel anastomosis. However, adverse reactions might occur under general anesthesia. The risk-benefit ratio is high in cases of patients who are not fully prepared for general anesthesia. Therefore, the axillary brachial plexus nerve block has been an alternative to general anesthesia. The advantages of plexus anesthesia are fewer anesthetic risks compared to general anesthesia. The catheter can be left in the axillae, which offers postsurgical pain treatment. There are also serious disadvantages, such as brachial plexus injuries or systemic toxicity, due to the high volume of anesthesia agent injection. (Power et al. 2010; Koscielniak-Nielsen et al. 2012) Recently, the introduction of the concept of hand surgery under wide-awake local anesthesia has lowered the anesthetic risks in finger replantation. (Lalonde DH. 2011) In this method, lidocaine is used for its rapid onset. It is combined with epinephrine for its vasoconstriction effect. In my experience, one or two milliliters of lidocaine is usually sufficient to achieve adequate digit anesthesia within several minutes.

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Proper patient selection is necessary for successful finger replantations under wide-awake local anesthesia. Patients should be psychologically stable and cooperative for an absolute immobilization of the affected limb during the process of microvascular reconstruction. Since the patient is awake during the operation, the surgical procedures should be explained to the patient before the operation. As prolonged operation time will increase the discomfort and even anxiety of the patient, only cases with an estimated operation time of fewer than three hours should be considered. This requires thoughtful patient selection as well as mature surgical replantation skills. In my study, the mean operation time in the wide-awake local anesthesia group is 142.8 minutes, compared to the general anesthesia group with 235.7 minutes ($p<0.05$) **(Fig. 4)**. This fact shows that our department selected patients accurately for the wide-awake local anesthesia and general anesthesia groups. At the same time, the different mean operation times of the two groups indicate problems when it comes to the comparability of the groups. It seems as if the general anesthesia group sustained more complex injuries, requiring a longer operation time and also affecting the success rate. Therefore, I only included single-finger injuries and excluded multiple-finger injuries to lower the effects of this bias. As a result, several criteria in patient selection for digit replantation surgery under wide-awake local anesthesia have been made in my study. These include

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single-digit replantation, absence of severe crush injury, estimated operation time of fewer than three hours, and a psychologically stable and cooperative patient with no associated life-threatening injury. I did not notice any necessary changes from wide-awake local anesthesia to general anesthesia in my patients. As the average operation time in single-digit replantation is about four to six hours in the hands of inexperienced microsurgeons, finger replantation under wide-awake local anesthesia by inexperienced microsurgeons is not justified.

The high survival rate of replanted fingers in this series shows that finger replantation under wide-awake local anesthesia does not affect the success rate. The three failures in the wide-awake local anesthesia group occurred in combination with other problems. One patient started smoking again after the operation, which could interfere with the success of the replantation. Another one had an infection (methicillin-resistant *Staphylococcus aureus*), and the third one failed in combination with early termination of chemical leech therapy, which had been conducted. These factors might interfere with the outcome and, therefore, should be mentioned. In the general anesthesia group, no possible factor of influence was noted.

In 2015, Lalonde showed the possibility of wide-awake local anesthesia without a

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tourniquet in hand surgery. (Lalonde D. 2015) He lists many advantages, such as lesser preoperative preparation, shorter hospital stays, less sedation or anesthetic risk, as well as many more. Today, this approach is widely accepted. (Gunasagaran et al. 2017; Steiner et al. 2018) In his approach, Lalonde uses a combination of lidocaine for anesthesia and epinephrine for hemostasis without a tourniquet. The main arguments against the tourniquet around the upper arm are the discomfort for the awake patient and the hemostasis can be ensured by epinephrine. In cases of urgently required finger replantation, epinephrine might impair microsurgical anastomosis. Vessel anastomosis plays a crucial role in replantation surgery. Epinephrine with its vasoconstrictor effect would impede the surgeon as it is harder to perform microvascular anastomosis. For this reason, I use a digit tourniquet instead of epinephrine, which is placed around the finger base near the level of the metacarpophalangeal joint. This has two advantages: first, the tourniquet lays within the anesthetic area, and second, the temporality control of bleeding in the operation field during the surgery. Therefore, I recommend wide-awake local anesthesia with a temporary tourniquet around the finger base in digit replantation.

The postoperative hospital stay depends on the condition of the replant and the patient's ability to self-care. In cases of unavailable venous reconstruction, patients require intrareplant heparin injection to ensure dermal bleeding for seven days and

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hospitalization is mandatory. Wound infection, unstable perfusion, venous congestion, or other perioperative problems might need immediate treatment or extensive care during the hospital stay. I think it’s feasible that while still being inpatients, my patients are more likely to avoid unnecessary risks, such as premature mobilization or smoking. In this part of the study, the treatment either with wide-awake local anesthesia or general anesthesia shows no significant difference in regard to the length of hospital stay. This is comprehensible since both angiogenesis and the wound-healing process take the same amount of time in the wide-awake local anesthesia and general anesthesia groups.

There are several advantages of finger replantation under wide-awake local anesthesia. Replantation can be performed in a shorter waiting period due to a lack of need for gastric preparation, as in general anesthesia. There is the possibility of rapid sequence intubation though. Nevertheless, rapid sequence intubation is not an adequate procedure with a finger replantation due to its possible risk of a so-called “cannot intubate cannot ventilate situation.” In this part of the study, the waiting time for patients receiving wide-awake local anesthesia was significantly shorter compared to general anesthesia (165.4 minutes versus 202.7 minutes; $p = 0.05$) **(Fig. 3)**. Consequently, the waiting anxiety of the patient and ischemia time of the amputated

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digit can be shortened. I would like to point out that the waiting time correlates with not only the gastric preparation in general anesthesia but also the operation room and surgeon availability. At least, I am trying to shorten the waiting time by using wide-awake local anesthesia. In my experience, the patient should undergo the replantation as soon as possible in terms of less pain and stress for the patient during the preoperative waiting period.

Furthermore, the vasodilatation effect of the local anesthetic agents can facilitate microcirculation and provide better perfusion of the replanted digit postoperatively. Replantation under wide-awake local anesthesia could enable the awake patient to play a role during the operation, achieving a better understanding of the procedures and the severity of the injuries through a video image on an electronic display monitor. In fact, it helps to improve the doctor-patient relationship. Patients will usually show greater appreciation after working together with the surgeons to achieve the success of replantation. (Teo et al. 2013; Rhee et al. 2017) Another advantage of finger replantation under wide-awake local anesthesia is the reduced medical expenses compared to other methods of anesthesia, although there is an absence of significant difference in the hospital stay between the two groups.

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However, there are some disadvantages to wide-awake replantation surgery. Patients might feel discomfort or anxiety. (Lied et al. 2017) They might violate aseptic principles during the operation, distract the attention of the surgeon, and thereby increase the risk of replantation failure. Although an empty stomach is not required under wide-awake local anesthesia, an empty urinary bladder is mandatory.

3.4 Injury severity grading system

Microvascular surgery makes digit replantation feasible; however, the reported attempt rate was suboptimal, and the survival rate varied widely. (Cho et al. 2018; Billington et al. 2021) To replant or not to replant, that is the question. Some surgeons displayed relative indications and relative contraindications; deciding replantation versus not replantation is not always easy and depends mainly on the surgeon in charge. Due to differences in medical insurance systems and cultural backgrounds, Asia patients have a stronger will to undergo replantation, and Asia surgeons are more willing to perform replantation even in severely injured amputations. (Tang et al. 2017) Based on my 20-year experience, I focus on the injury severity of the amputation tissue evaluated at the emergency department. Without practical grading scores of the injury severity, physicians are not able to communicate between medical personnel, record the tissue condition by writing down, and compare replantation attempt rates or treatment

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outcomes.

The proposed severity score system for digit amputation composes the structures of the bone, joint, extensor tendon, flexor tendon, artery, nerve, vein, and soft tissue envelope. This sequence is also my preference for repairing orders during the replantation surgery, and it helps the surgeon to systemically evaluate the tissue quality before entering the operation room. In general, the bigger the number assigned to each item means more severe the traumatic injury of the tissue and requires the more advanced surgical technique to repair it. The score distance between each item is not equal for sure due to the different nature of the injured tissue, and the score should not sum up.

Firstly, the bone and joint are taken into consideration together **(Figure 7)**. When the patient presents at the emergency department, his injured hand and the amputated part should be checked with an X-ray on the same film. Any bony fragment should be carefully identified before entering the operation room. If presenting significant bone fragments, it is usually not easy to achieve perfect bone reduction and fixation, leading to prolonged immobilization and poor tendon gliding; and it holds a greater risk of bony malunion or nonunion after the survival of the replanted digits. (Morrison et al. 2007) In

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the case of significant segmental bone loss (i.e., it stands for more severe injury during the trauma), shortening osteosynthesis will facilitate the tension-free neurovascular repair and rid nerve or vascular grafting. However, it may result in an imbalance between the flexor and extensor tendon and suboptimal motor function. In cases the joint is involved, poor range of motion would be expected reasonably as the consequence of ankyloses after the survival of the replanted digit.

Secondly, the extensor and flexor tendons are evaluated after the skeleton **(Figure 8)**. Due to their resilient nature, they tend to suffer from avulsion injury rather than crush injury in a forced amputation injury. Rupture of the musculotendinous system always occurs at the weakest point, depending on the traumatic force direction and strength during the insult. The presenting disruption at the musculotendinous junction indicates a big trauma zone, and poor tendon gliding function will be expected reasonably as the consequence of adhesion in the healing process. Furthermore, in the tendon suffering from segmental injuries or tendon loss, the surgeons would require tendon grafting or tendon transferring in the following reconstruction procedures. It is important to remember that good functional recovery is greatly dependent on these early steps of skeleton and tendons repair. (Dec W. 2006)

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Thirdly, the artery plays the most crucial role in achieving the survival of the replanted digit. This proposed grading system provides the surgeon gross evaluation of the digit artery at the emergency department preoperatively. However, the detailed examination of the digit artery is only feasible by operating microscopy in the operation theater. The presence of the red line sign or the ribbon sign indicates vessel damage from longitudinally transmitted injury, which may require vascular grafting, which is a sign of a poor prognosis. (Dec W. 2006) On the counterpart, the artery of the amputated stump is as crucial as the distal part, and a strongly arterial spurt indicates good inflow pressure. No replanted digit will survive without a reliable feeding artery reconstruction. Next to the artery, the digit nerve always hitchhikes it and usually suffers from a similar degree of injury. **(Figure 9)** From my experience, the digit nerves are more resilient than arteries, and they present more avulsion injuries consequently.

Last but not least, the part of digit replantation is the vein and soft tissue envelope **(Figure 10)**. The sizable veins develop proximally from the nail root and locate subcutaneously. They are fragile and are suffered from the same severity of the injury with the skin parallelly. In cases of lacking suitable veins during replantation, some surgeons advise leech therapy as an alternative to venous reconstruction. (Barnett et al. 1989; Yokoyama et al. 2007; Beier et al. 2010) However, good venous repair reduces

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blood loss from leech therapy and alleviates nursing care in salvage procedures. (Woo et al. 2015) In presenting the skin ecchymosis or multiple irregular lacerations, crush injury of the soft tissue is evident. It will induce a severe inflammatory response and holds a poorer prognosis by delaying vascular thrombosis. Furthermore, worse scar conditions will also be expected after the wound healing in the survived to replant digit.

There are some limitations regarding this grading system. It does not reveal the patient's comorbidity, smoking status, ischemia time of the amputated segment, and the one's motivation. These factors influence the treatment outcomes to some degree. Since the ultimate goal of replantation surgery is to restore the form and function of the hands, this evaluation system scores on the better one of the dual structures, such as digit arteries or digit nerves. From this viewpoint, it provides information on the recovery possibility rather than the extent of the amputation injury. Furthermore, this digit amputation grading system also can be utilized in digit injuries with incomplete amputation. The structure presents no significant trauma and deserves no surgical repair would score as zero. It is worth mentioning that the smaller the number means lesser the traumatic injury of the tissue, but it is no guarantee of good treatment results. The good results come from detailed assessment, excellent surgical technique, delicate postoperative care, and aggressive rehabilitation therapy.

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Chapter 5: PROSPECTIVES

The hands are the most important organ that outputs human high technology and civilization. They are also vulnerable to injury due to their anatomic position and laborious task. Most people make money and maintain one's subsistence by their hands. That means in cases of a hand injury, he would lose his ability to work and consequently interrupted income. From the socioeconomic viewpoint, saving a traumatic hand is as meaningful as saving one's life and saving a family. This heavy responsibility and privilege deserve to hand surgeons who have the ability to restore hand function as well as possible. I am very glad to be a plastic surgeon and advocate myself in this reconstruction field.

The anatomic structures of hands are very unique and delicate. It is not easy to recover from a traumatic hand. Reviewing the management of traumatically amputated fingers or the thumb, the attempt rate of replantation is suboptimal. The reasons for the low attempt rate of digit replantation include poor medical accessibility, low reimbursement, the time-consuming procedure for complicated injuries, and unavailability of surgeons or surgical facilities. On the other hand, the survival rate of digit replantation varies from hospital to hospital. The wide range of the survival rate

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discloses that digit replantation highly depends on the surgeon's skill and intensive post-operative care. To improve the attempt rate and survival rate of digit replantation, I focus my research on overcoming vascular difficulties and simplifying surgical anesthesia.

The first part of my research is to try my best to save the distal digit amputation. Fingertips are beyond the distal interphalangeal joints and are defined as the terminal ends of our hands. They are the most vulnerable part of hand trauma, especially amputation injury. The fingertip contains fingernail, distal phalanx bone, pulp tissue, tiny vessels, branched nerves, and glabrous skin with fingerprints. The above structures are very difficult to reconstruct in the digit amputation injury without replantation. Some surgeons tend to not replant the distal digit due to technical difficulty and poor survival rate. The major obstacle to fingertip replantation is no sizable vessel to repair, particularly vein. From my first part of the research, the replanted fingertip is able to survive as well based on a reliable artery repair solely. In other words, success in distal digit replantation is not dependent on venous anastomosis. This result encourages hand surgeons to replant the fingertip even without a sizable vein in the digit. It also enhances the attempt rate and survival rate of distal digit replantation.

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Since the success in distal digit replantation is not dependent on venous anastomosis but relay on a satisfied artery reconstruction, I expand this experience to treat venous congested digits after the primal replantation. A standard digit replantation consists of both artery and vein repair. However, venous problems will often encounter during the postoperative critical period. Traditionally, the patients who run into venous congestion after a standard digit replantation must return to the operation room for once more venous reconstruction. Nevertheless, the re-intervention vein usually fails again if the cause reason persists. The second part of my research is to improve the survival rate of digit replantation by external bloodletting therapy in congested replants. The external bloodletting therapy, also known as chemical leeching therapy, is executed easily at the bedside and does not take the patient back to the operation room. This method is effective and efficient in treating congested fingers after replantation surgery. In addition, I set up an algorithm for the management of congested digits after the primal replantation with a positive result in survival. It also provides a guideline for all medical personnel in our center to care for replanted digits with a standard quality.

The hand injury is always an accident and random. We cannot predict the injury severity and when the injury occurs. In the clinical scenario, the medical facility and the patient would not always be ready for the time-consuming replantation surgery. The

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patient who suffers from a traumatic amputation of his fingers usually has a long waiting period at the emergency department before the surgery takes place. To shorten the waiting period at the emergency room and make replantation more convenient, I adopt wide-awake local anesthesia to treat this kind of injury. The third part of my research discloses that digit replantation under wide-awake local anesthesia is feasible in the selected patients. This result encourages hand surgeons to replant a single digit with fewer anesthesia demands. In suitable circumstances, this method may be a game-changer for medical practice in digit replantation.

To replant or not to replant, that is the question. The low attempt rate and wide-ranged survival rate of digit replantation might attribute to the patient selection. Some surgeons indicated that the severely crushed or avulsed amputation digits are not suitable for replantation. But the question is how crush is severe crush and how avulsion is severe avulsion. So far, there is no practical grading system to evaluate the amputated part and the amputated stump of the hand. Lacking a practical grading system, we are unable to scientifically evaluate the injury severity of amputations preoperatively and treatment outcomes postoperatively. Thereafter, I developed an injury severity grading system for digit amputations. The fourth part of my research is to score the damaged tissue according to its injury severity in the traumatic amputation. In general, the

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bigger the number assigned to each item means more severe the traumatic injury of the tissue and requires the more advanced surgical technique to repair it. This part of the result enables surgeons to scientifically evaluate the injury severity, record the tissue condition by writing down, and compare the treatment outcomes.

The final goal of treating an injured hand is to restore the form and the function of the hand as well as possible. The aforementioned results of my works are to improve the attempt rate and survival rate of digit replantation in a rationalized and convenient way. Making the replanted digit survive in the acute critical period is merely the first step to achieving good outcomes. Success digit replantation is defined as the patient regains his fingers and the function of the hand. The patients would experience some problems after the survival of the replanted fingers. The late consequences of the replanted digits are stiff joints, insensitive fingertips, atrophic pulp, and irregular nails. The severity of the consequence is strongly correlated with the severity of the tissue damage on the amputated digits. This viewpoint reinforces the importance of setup a grading system for the injury severity of traumatic digit amputation. Further prospective of my work will focus on the correction of late consequences after the replants survival and on improving the treatment outcomes of digit amputation.

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5.1 Correction of the pulp atrophy

Atrophic change of the replanted digit pulp is one of the late sequences. In the same way that free vascularized tissue transfers, the replanted fingers or the thumb would experience some degree of tissue atrophy. It causes not only disfiguration but also functional impairment, such as a tight sensation, rest pain, decreased sensitivity, cold intolerance, and limited motion of the replanted digit. The degree of finger pulp atrophy is difficult to predict in the acute stage. It might strongly correlate with tissue damage from the trauma and with tissue hypoxia or ischemia in the perioperative period. Most surgeons think that finger pulp atrophy belongs to one of the wound healing processes and is a result of tissue fibrosis. So far, there is no effective way to reverse it.

Fat grafting is a surgical procedure in plastic surgery to correct tissue volume deficiency. Surgeons extract fat via liposuction technique, purify fat solution, and then inject fat into the destination. The transferred fat graft would reabsorb in a certain percentage; hence, repeated fat grafting is necessary to achieve satisfying volume restoration. I adopt this surgical technique to treat finger pulp atrophy after replantation in some patients. The preliminary results are positive and promising. There is no report on this topic in the literature review, and worth me to stick to it.

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5.2 Improving the treatment outcomes by specialty

It is a common mantra that getting the replanted digit to survive is only the first step of the healing process and achieving a good outcome in the treatment of a hand suffering from traumatic amputation. It has to emphasize that attempt surgically replant an amputated finger is the very beginning of this first step. Reasons for not replantation include poor medical accessibility, low reimbursement of this surgery, the time-consuming procedure for complicated injuries, inadequate training or confidence of the surgeon, and unavailability of surgical team or facilities. The thorough concept of my dissertation is trying to improve the attempt rate and survival rate of digit replantation. My prospective is to keep this concept working for the rest of my career.

Generally speaking, the most important factor for replantation attempts is the surgeon's enthusiasm. And the most important factor for replantation survival is the surgeon's experience and technique. Digit replantation is a highly surgical technique demand, and a long learning curve is required. This replantation surgery is not to be undertaken without a serious commitment to the endeavor. As with all other skills, more surgical practice makes outcomes more perfect. A traumatically amputated digit will receive professional treatment from a well-skilled and ardent surgeon. Treatment of amputated fingers or the thumb should be regarded as a specialty of medicine. Like

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traumatology or burn medicine, the amputated digits should be treated in a replantation center. Regionalization and centralization to care for traumatic hands will improve the replantation rate and survival rate; hence, the patients will have better outcomes.

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SUMMARY

This dissertation is an important result of my 20-year hard work in plastic surgery. The core concept of this dissertation is to improve the treatment outcomes of traumatically amputated fingers or the thumb. There are four sequential parts in this dissertation that represent the ways how I surgically treat the traumatic digits; step by step, and achieve excellent outcomes. My experience in this field will be helpful for future surgeons in treating hand trauma, especially amputation injuries. These accomplishments are summarized in the following paragraphs.

The first part of my dissertation showed that the overall success rate of distal digital replantation was 81 percent, and no differences in the survival rates between replantations with and without venous anastomosis were observed. The structures in the fingertips or thumb tip are extremely tiny, and most surgeons have clearly abandoned all pretense of trying to replantation. The major obstacle to distal digit replantation is no sizable vessels for reconnection, especially the vein. This part of the results indicates that the success of distal digital replantation is not dependent on venous anastomosis and suggests that replantation should be encouraged in cases of complete distal digital amputation even without venous anastomosis. By the way, the survival rate is poor in

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cases without arterial reconstruction of the replanted digit (i.e., composite grafting). This part would increase replantation attempts in the distal digit amputation while emphasizing the importance of digit artery repair in replantation surgery.

To increase the survival possibility of digit replantations and to improve the quality of replantation care, the second part of my dissertation is the management of venous insufficiency in the replanted digits. Postoperative venous congestion is a crucial cause of digit replantation failure. Early detection and efficient treatments of venous problems are paramount. Irreversible tissue damage occurs in cases of delayed or ineffective treatments. At times when the clinical conditions for surgically venous re-anastomosis are unmet (either insufficient gastric preparation or unavailable medical crew), external bloodletting offers a timely alternative treatment with positive results. External bloodletting minimizes any treatment delay, and it also tends to result in a higher survival rate than surgically venous re-anastomosis. However, potential blood loss should keep in mind when conducting this therapy. A successful venous reconstruction once again would provide superior venous blood drainage and alleviate the possibility of a postoperative blood transfusion. Therefore, I advocate a treatment algorithm for venous congestion in digit replantations. It helps our team members to treat this condition efficiently and keep state-of-the-art replantation care. This part of the

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achievements would increase the survival rate of replantation surgery, especially encountering venous congestion during the postoperative critical period.

To facilitate the process of digit replantation, my effort is to reduce the medical demand for this surgical procedure. The third part of my work in this dissertation is to simplify surgical anesthesia in digit replantation. I reported my clinical experience of fingers or thumb replantation under wide-awake local anesthesia surgery, with a success rate of 81.25 percent, which is no significant difference compared to that under general anesthesia. The key point to successful digit replantation under wide-awake local anesthesia is proper patient selection. I recommend digit replantation under wide-awake local anesthesia in certain indications. These include single-digit amputation, absence of severe crush injury, estimated operation time of fewer than 3 hours, and a psychologically stable and cooperative patient with no associated life-threatening injury. Wide-awake local anesthesia is able to shorten the waiting period before the operation, minimize waiting anxiety and pain, and reduce medical expenses. This part of the accomplishments shows it is feasible to replant a broken digit under wide-awake local anesthesia. This procedure is more convenient for both the patient and the surgeon; therefore, it would furthermore improve the replantation attempt rate.

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The last part of my work in this dissertation is to build up a grading score system for the amputation severity evaluation. By detailed evaluation of each repair-demanding structure and making a score of each item, physicians can document the injury severity more scientifically. The more severely damaged structure in the amputation would correspond with the bigger the number assigned and require the more advanced surgical technique to repair it. It is important to note that the functional outcomes after treatment are determined by the bone, joint, tendons, and skin. At the same time, the survival of the replanted digit is determined by the artery and soft tissue condition. More important, it is no guarantee of good treatment outcomes in less damaged tissue with a smaller number assigned from the digit amputation. The good results assuredly come from detailed assessment, excellent surgical technique, delicate postoperative care, and aggressive rehabilitation therapy. This part of my work, building a good severity score system, will rationalize attempt rates and survival rates of the digit replantation by preventing bias from the patient selection. It certainly provides a reference level for the treatment outcomes.

Being a plastic and reconstructive surgeon, I devote myself to microvascular surgery for traumatic hand reconstruction. All my effort in this field is to save every hand injury, to improve treatment outcomes, and to minimize the patient's suffering.

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From the socioeconomic viewpoint, saving a traumatic hand is as meaningful as saving one's life and saving a family. This heavy responsibility and privilege deserve to hand surgeons who have the ability to restore hand function as well as possible. I am very proud to be a plastic surgeon and advocate myself in this reconstruction field. This dissertation has four sequential parts including successful distal digit replantation without vein repair, external bloodletting to save venous congestion after replantation, digit replantation under wide-awake local anesthesia, and an injury severity grading system for digit amputations. It records my efforts and my achievements in digit replantations. I will keep my promise to treat every hand injury with state-of-the-art medical techniques. The methods in this dissertation will also help hand surgeons to treat amputated digits in the future.

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FIGURES

Figure 1. Venous congestion occurred after replantation (left). The digit color was restored from dark deoxygenated blood to fresh oxygenated blood through external bloodletting therapy (right).

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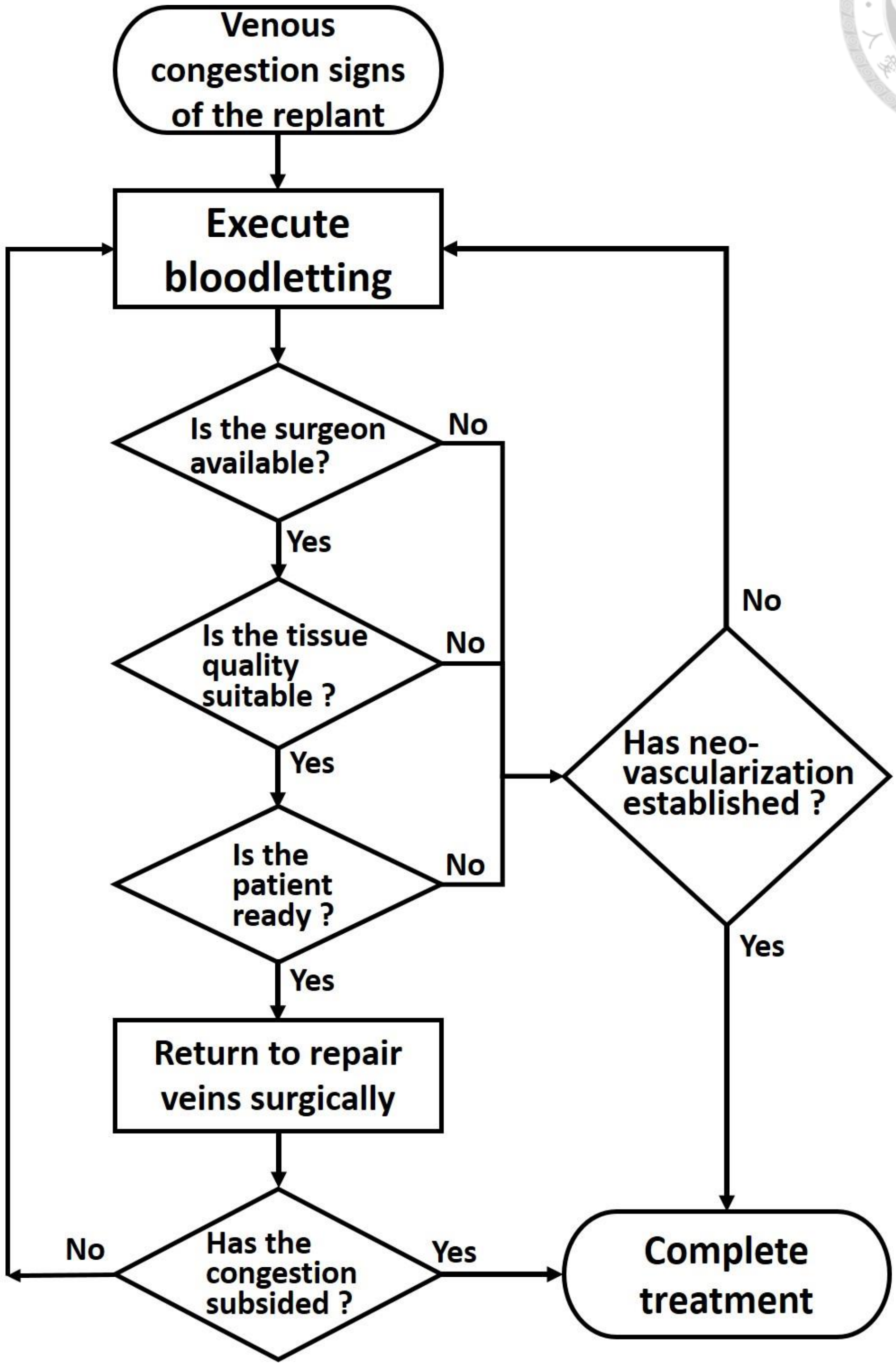

Figure 2. Treatment algorithm for venous congested digits after replantations.

doi:10.6342/NTU202202540

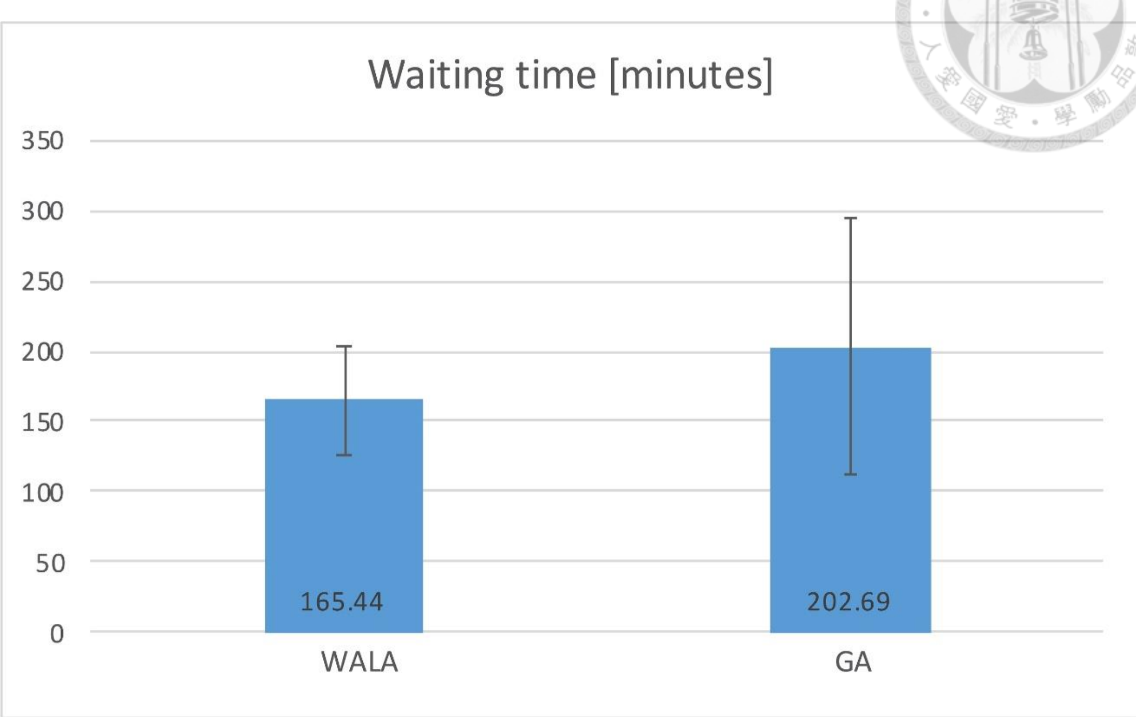

Figure 3. Waiting time (p=0.05)

doi:10.6342/NTU202202540

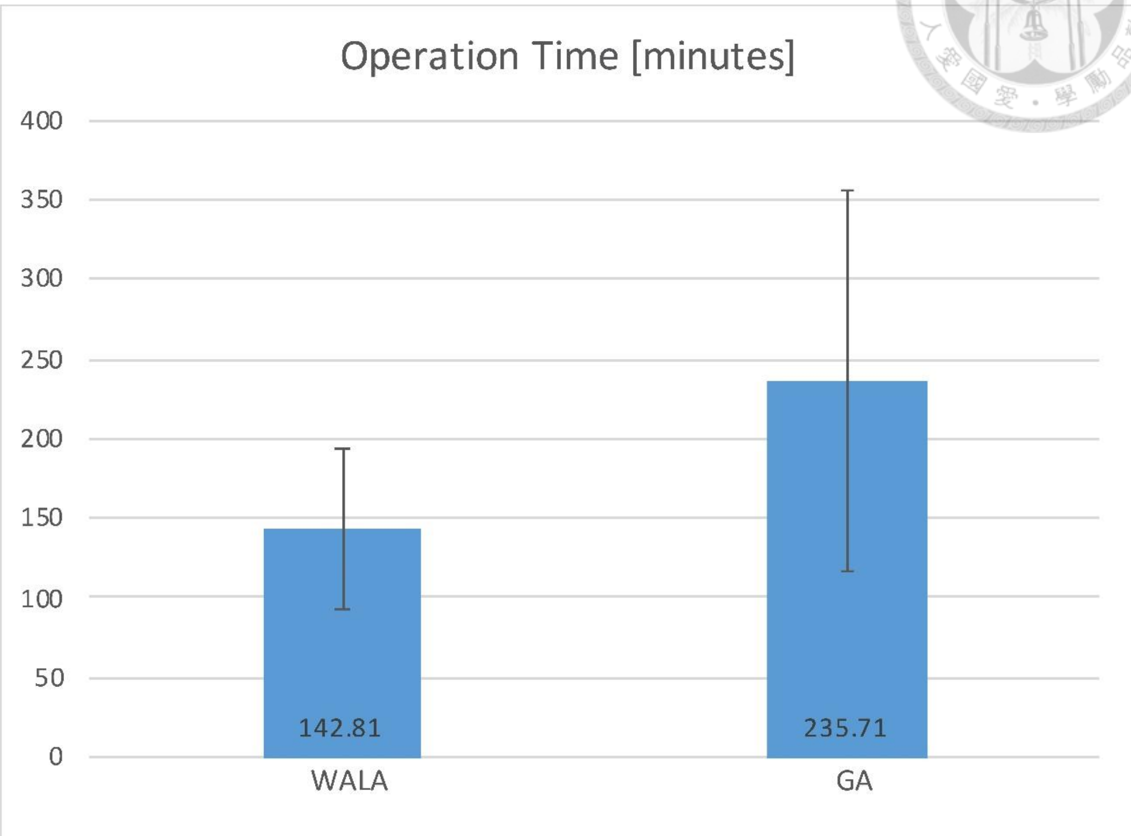

Figure 4. Operation time ($p<0.05$)

doi:10.6342/NTU202202540

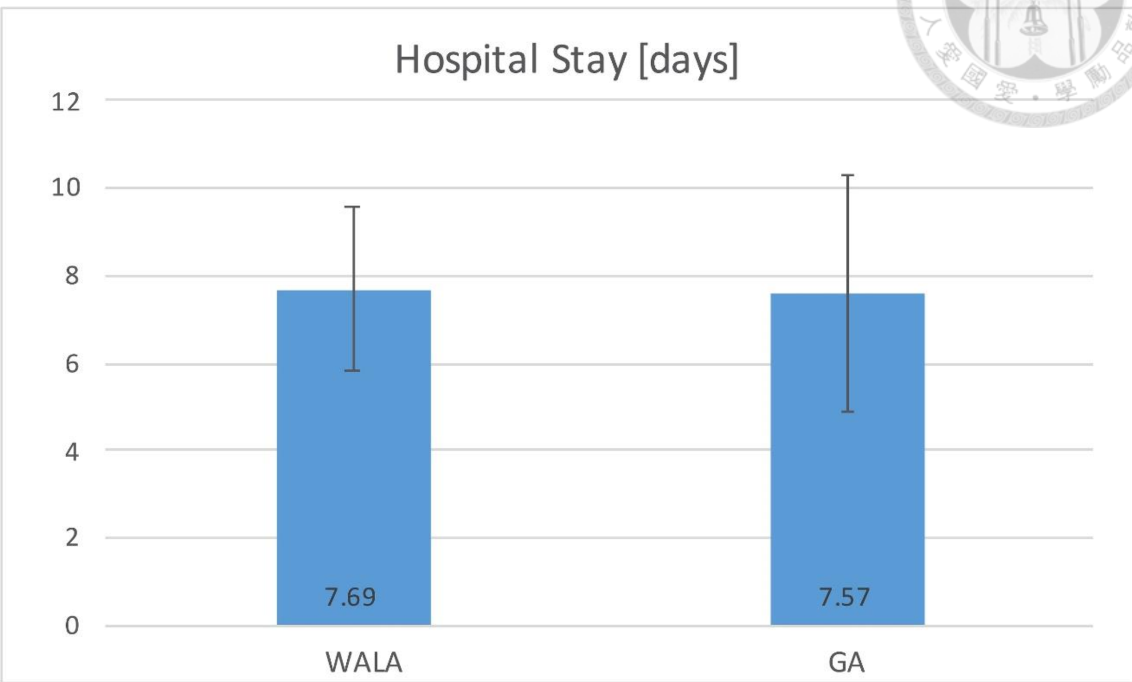

Figure 5. Hospital stay (p=0.86)

doi:10.6342/NTU202202540

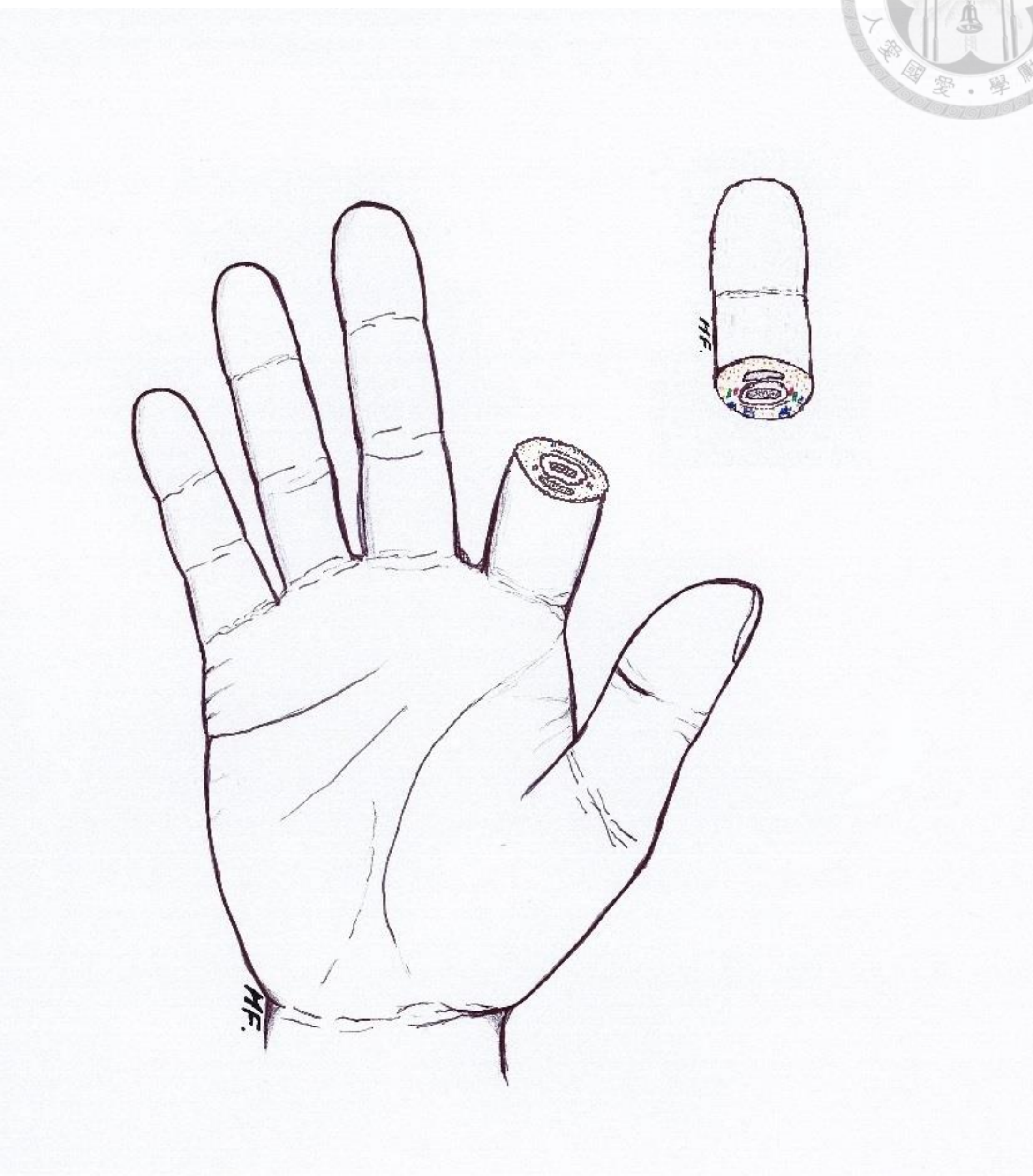

Figure 6. A sharp-cut amputation of a finger. The injury severity of structures in this amputation is grade one.

doi:10.6342/NTU202202540

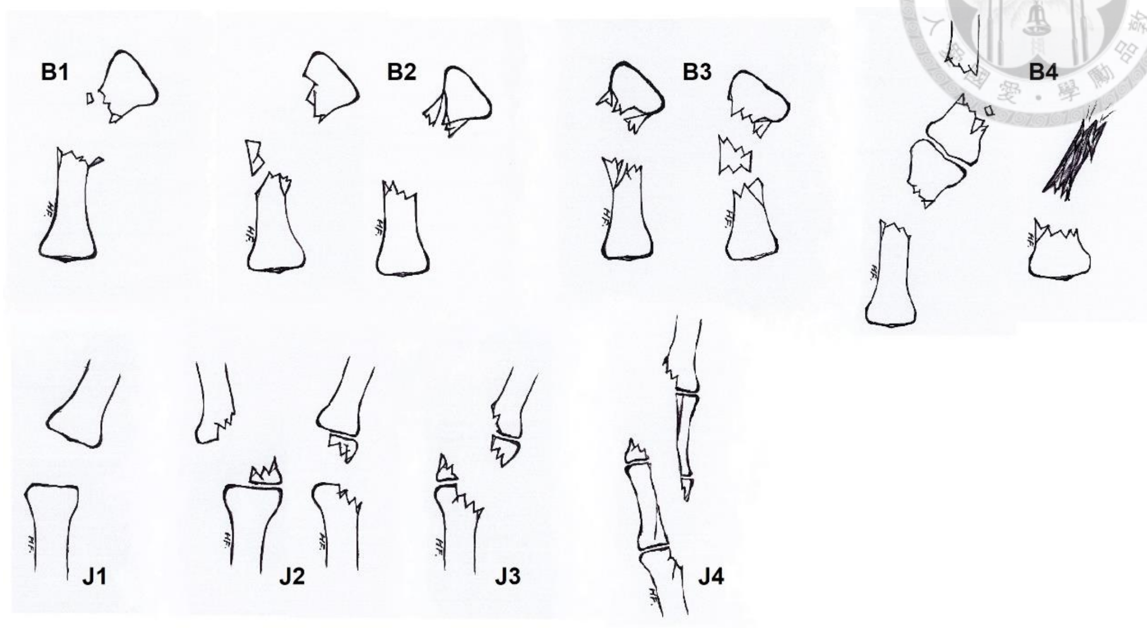

Figure 7. The injury grading for bone and joint from grade one to grade four.

doi:10.6342/NTU202202540

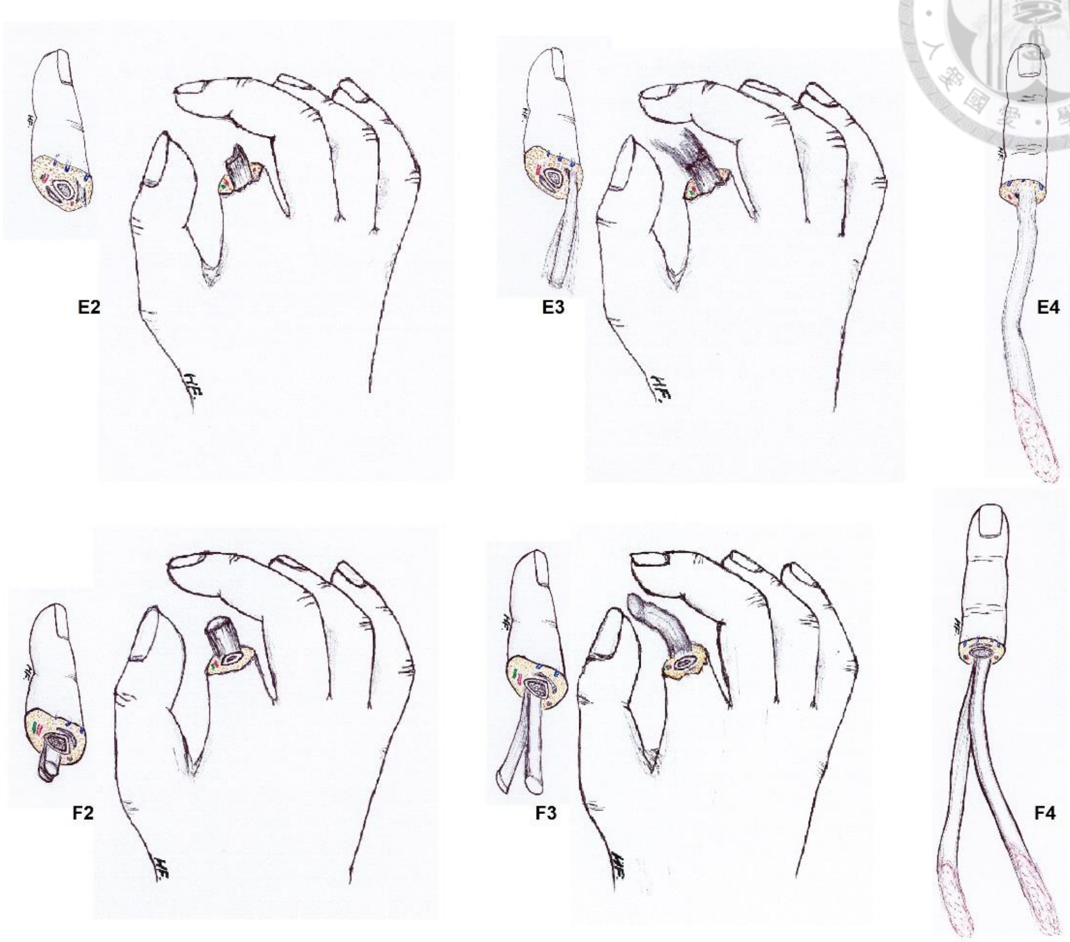

Figure 8. The injury grading for extensor and flexor tendons from grade two to grade four. The traumatic injury of a tendon disruption would be avulsed either distally or proximally.

doi:10.6342/NTU202202540

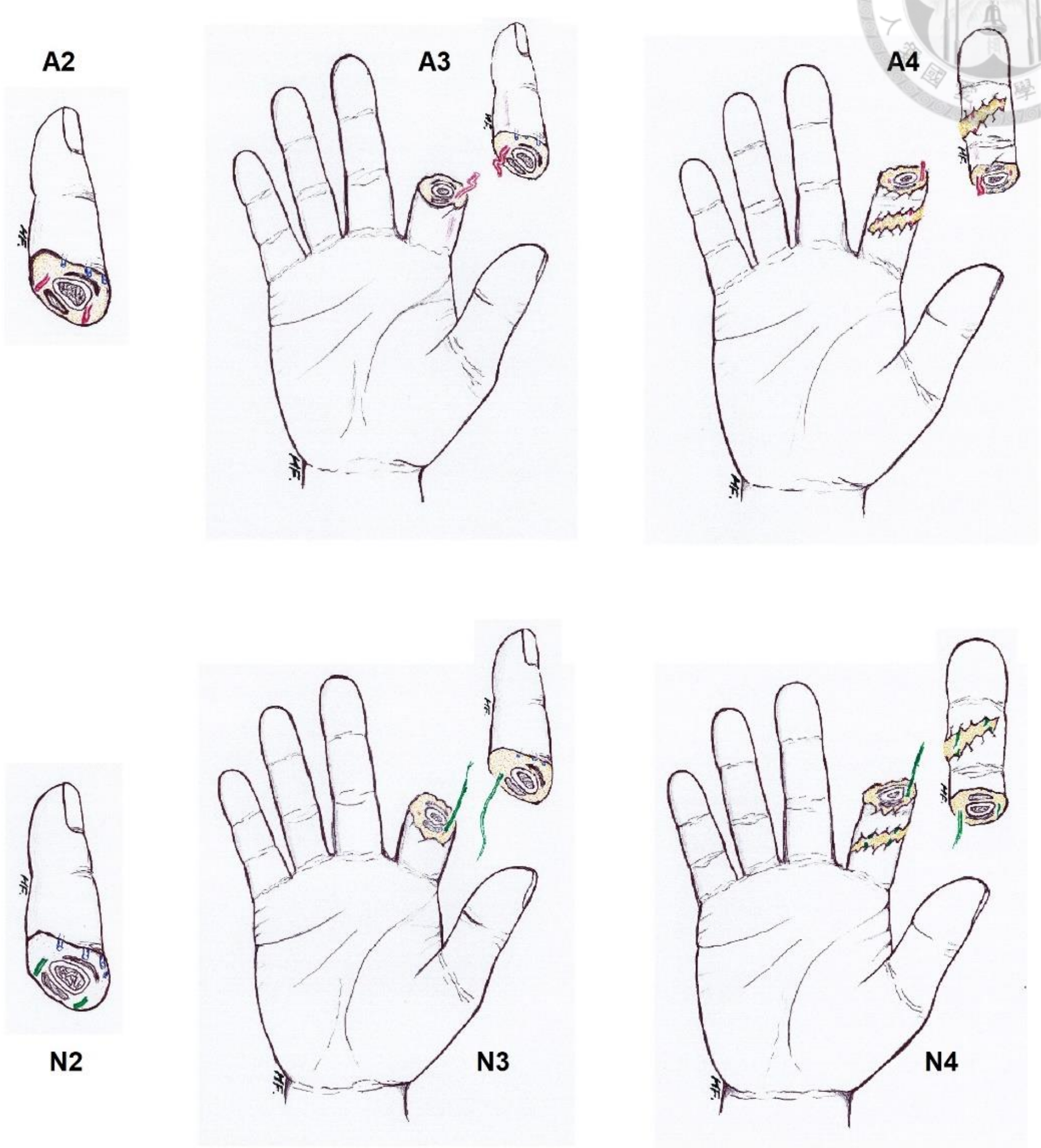

Figure 9. Grade two to grade four injury severity for the artery and nerve in a digit amputation. The red line sign or ribbon sign indicates longitudinally avulsed injury of the artery. The traumatic injury of a nerve or artery disruption would be avulsed either distally or proximally.

doi:10.6342/NTU202202540

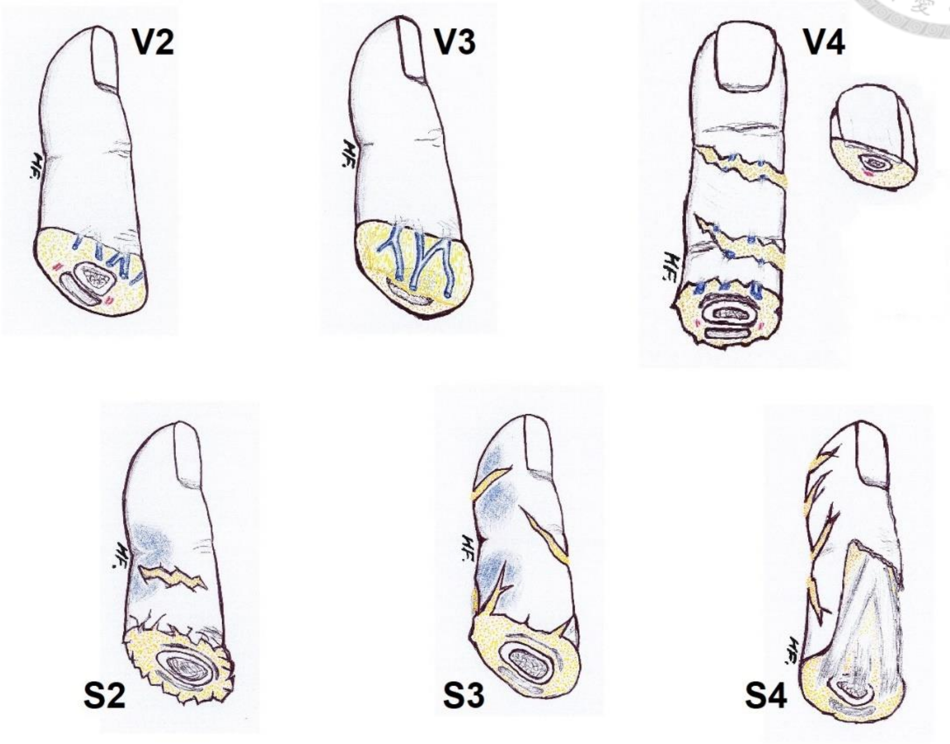

Figure 10. The injury grading for veins and skin from grade two to grade four. There would be no sizable vein in digit tip amputation.

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TABLES

Table 1. Survival rate in three different groups of salvaged digits

Group	No. of Salvaged Digits	No. of Surviving Digits	Survival Rate (%)
A	16	13	81.3
B	11	9	81.8
C	4	0	0

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Table 2. Patients' characteristics and digits condition of surgically venous re-anastomosis for the treatment of venous congestion (Group A)

Case	Age, Gender	Level of injury	No. of repaired vessels	Replantation time (min)	Onset of venous congestion (h)	Waiting time to OR (min)	Post-op Transfusion	Re-operation time (min)	Survived
1[a]	29 y/o, female	L ring, PIP joint L small, PIP joint	1A, 2V 1A, 1V	455	22 ring finger	158	2U pRBC	245 [b]	No No
2	51 y/o, male	L index, middle phalanx	2A, 2V	240	43	122		155	Yes
3[a]	22 y/o, male	R index, PIP joint R thumb, MP joint	2A, 2V 1A, 2V	570	38 index finger	165	2U pRBC	138 [b]	No Yes
4	37 y/o, male	R index, proximal phalanx	2A, 3V	306	61	135	2U pRBC	150	Yes
5	47 y/o, female	L long, distal phalanx	1A, 1V	122	9	210		226 [b]	No
6	73 y/o, male	L long, DIP joint	2A, 1V	248	23	102		125	Yes
7	25 y/o, male	R index, DIP joint	1A, 1V	449	8	175		190 [b]	No
8	32 y/o, male	L small, proximal phalanx	1A, 2V	205	17	228	2U pRBC	203 [b]	No
9	41 y/o, male	R ring, PIP joint	2A, 2V	237	33	195		181 [b]	Yes
Mean	39.7 (7:2)			257.78 / digit	28.22 / digit	165.56	0.89 / digit	179.2 / digit	44.4% (4/9)

min: minutes, h: hours, y/o: years old, L: left, R: right, PIP: proximal interphalangeal, IP: interphalangeal, DIP: distal interphalangeal, A: artery, V: vein

a. Case 1 and 3 received two-finger replantation. One of the replanted fingers developed venous congestion postoperatively.

b. Venous reconstructions with a segment of vein graft (7 out of 9 patients)

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Table 3. Patients' characteristics and digits condition of external bloodletting therapy for the treatment of venous congestion (Group B)

Case	Age, Gender	Level of injury	No. of repaired vessels	Replantation time (min)	Onset of venous congestion (h)	Post-op Transfusion	Treatment duration (d)	Survived
10	52 y/o, female	L thumb, IP joint	1A, 2V	300	62		5	Yes
11	60 y/o, male	L index, PIP joint	1A, 1V	210	10		6	Yes
12[a]	42 y/o, female	R ring, middle phalanx R long, middle phalanx	2A, 2V 2A, 2V	405	31 R ring finger	4U pRBC	6	Yes Yes
13	87 y/o, female	L ring, distal phalanx	1A, 1V	138	57		5	Yes
14	57 y/o, female	L ring, DIP joint	2A, 1V	160	19	4U pRBC	7	Yes
15	41 y/o, male	R index, distal phalanx	1A, 1V	180	28	2U pRBC	6	No
16	38 y/o, male	L thumb, proximal phalanx	1A, 2V	128	11		6	Yes
17	53 y/o, male	R thumb, IP joint	1A, 1V	457	18	6U pRBC	7	Yes
18	31 y/o, male	R index, middle phalanx	1A, 2V	295	23	2U pRBC	4	No
19	60 y/o, male	L small, proximal phalanx	2A, 2V	300	55	4U pRBC	6	Yes
20	24 y/o, male	R long, PIP joint	1A, 2V	274	13		6	Yes
21	35 y/o, male	R thumb, proximal phalanx	2A, 2V	383	21	4U pRBC	7	Yes
22	29 y/o, male	L small, PIP joint	1A, 2V	290	15	2U pRBC	6	Yes
Mean	46.9 (9:4)			255.23 / digit	27.92 / digit	2.15 / digit	5.92 / digit (4-7)	84.6% (11/13)

min: minutes, h: hours, d: days, y/o: years old, L: left, R: right, PIP: proximal interphalangeal, IP: interphalangeal, DIP: distal interphalangeal, A: artery, V: vein
a. Case 12 received two-finger replantation and only ring finger developed venous congestion postoperatively.

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Table 4. Statistical comparison between group A and group B

	Group A Mean (SD)	Group B Mean (SD)	P-value
Age (yr)	39.67 (15.82)	46.85 (17.06)	0.2559[a]
Replantation time (mins)	257.78 (88.45)	255.23 (97.31)	1.00[a]
Onset of congestion (h)	28.22 (17.25)	27.92 (18.25)	0.9202[a]
Post-op transfusion (pRBC)	0.89 (1.05)	2.15 (2.08)	0.1626[a]
Waiting time (mins)	165.56 (41.47)	-	
Re-operation time (mins)	179.22 (40.74)	-	
Treatment duration (d)	-	5.92 (0.86)	
Survival rate (%)	44.4	84.6	0.0743[b]

a. Mann Whitney Test

b. Fisher's exact test

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Table 5. Patients' characteristics and digits condition that was complied with the algorithm for the treatment of venous congestion

Case	Age, Gender	Level of injury	No. of repaired vessels	Replantation time (min)	Onset of venous congestion (h)	Post-op Transfusion	Treatment duration (d)	Survived
23	27 y/o, male	R long, PIP joint	1A, 2V	225	16		6	Yes
24	39 y/o, male	R index, middle phalanx	1A, 1V	262	9	2U pRBC	7	Yes
25	66 y/o, male	L thumb, IP joint	1A, 2V	317	26	2U pRBC	5	Yes
26	43 y/o, male	L index, DIP phalanx	1A, 1V	146	12		7	Yes
27	56 y/o, female	L ring, proximal phalanx	2A, 2V	325	30	4U pRBC	8	Yes
28[a]	25 y/o, male	R thumb, proximal phalanx	1A, 2V	273	28	2U pRBC	2	Yes
29	47 y/o, male	L small, PIP phalanx	1A, 1V	195	35		5	Yes
30	31 y/o, male	R thumb, IP joint	1A, 2V	280	18	2U pRBC	6	Yes
Mean	41.8 (7:1)			252.88 / digit	21.75 / digit	1.50 / digit	5.75 / digit (2-8)	100% (8/8)

min: minutes, h: hours, d: days, y/o: years old, L: left, R: right, PIP: proximal interphalangeal, IP: interphalangeal, DIP: distal interphalangeal, A: artery, V: vein

a. Case 28 underwent returning operation theater and venous reconstruction with a segment of vein graft. The treatment duration of external bloodletting was two days.

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Table 6. Results of digits replantation between WALA group and GA group.

	Sex (M:F)	Age (years)	Waiting Time (min)	Operation Time (min)	Hospital Stay (days)	Success Rate (%)
WALA						
Mean	13:3	39.69	165.44	142.81	7.69	81.25
SD		14.69	39.00	50.03	1.89	
GA						
Mean	26:9	44.49	202.69	235.71	7.57	74.29
SD		17.70	91.24	119.85	2.70	
p	0.73*	0.33#	0.05#	<0.05#	0.86#	0.73*
Overall		42.98	190.88	206.57	7.61	76.47

WALA, wide-awake local anesthesia; GA, general anesthesia.

*Fisher’s exact test.

#*t* test.

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Table 7. Wide-awake local anesthesia group

Patient No.	Sex	Age (years)	Waiting time (min)	Operation time (min)	Hospital Stay (days)	Outcome
1	Male	57	153	95	7	
2	Male	46	230	130	7	
3	Male	34	121	200	10	Fail (infection)
4	Male	27	202	68	8	
5	Female	19	152	107	7	
6	Male	42	199	150	9	
7	Female	56	175	156	8	
8	Female	25	194	170	8	
9	Male	30	132	66	7	
10	Male	18	220	154	5	
11	Male	42	99	115	9	
12	Male	23	126	250	3	
13	Male	60	181	210	7	
14	Male	40	104	180	10	Fail (smoking)
15	Male	52	175	95	11	Fail (early termination)
16	Male	64	178	139	7	
Mean	**13:3**	**39.69**	**165.44**	**142.81**	**7.69**	**81.25 %**
SD		**14.69**	**39.00**	**50.03**	**1.89**	

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Table 8. General anesthesia/Control group

Patient No.	Sex	Age (years)	Waiting time (min)	Operation time (min)	Hospital Stay (days)	Outcome
1	Male	53	432	271	7	Fail
2	Female	39	125	205	8	
3	Male	33	321	295	3	
4	Male	56	140	157	4	
5	Male	47	414	102	8	
6	Male	23	226	449	9	
7	Male	23	132	355	9	Fail
8	Female	87	245	138	8	
9	Female	37	237	180	11	
10	Male	54	134	260	7	
11	Male	26	112	133	3	Fail
12	Male	37	178	299	17	
13	Male	55	101	455	9	
14	Male	40	118	360	7	
15	Female	26	122	340	8	
16	Male	41	385	55	7	Fail
17	Male	73	155	248	6	
18	Male	41	157	86	7	Fail
19	Male	21	267	334	7	Fail
20	Female	57	146	160	10	
21	Male	59	96	348	8	
22	Male	55	155	103	7	
23	Male	25	149	155	7	
24	Male	76	359	150	6	
25	Male	26	167	572	11	
26	Female	35	139	240	2	Fail
27	Female	50	178	210	10	
28	Female	49	119	245	7	
29	Male	39	162	104	8	
30	Male	51	191	182	6	
31	Female	71	226	191	6	
32	Male	71	186	73	8	
33	Male	5	323	309	6	Fail
34	Male	38	204	362	12	Fail
35	Male	38	293	124	6	
Mean	**26:9**	**44.49**	**202.69**	**235.71**	**7.57**	**74.29 %**
SD		**17.70**	**91.24**	**119.85**	**2.70**	

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Table 9. Grading system for a complete finger or thumb amputation

	Grade 1	Grade 2	Grade 3	Grade 4
Bone	B1 Simple fracture with or without minor fragment	B2 Fracture with significant fragment on one side	B3 Fracture with significant fragment on both sides	B4 Segmental fracture with or without bone loss
Joint	J1 Simple disarticulation	J2 Intra-articular fracture on one side	J3 Intra-articular fracture on both sides	J4 Contiguous two-joint fracture
Extensor	E1 Sharp cut with clear tendon edge	E2 Blunt disruption with irregular tendon edge	E3 Disruption edge away from the amputated site > 2cm	E4 Disruption from MT junction*; Segmental tendon injury or loss
Flexor	F1 Sharp cut with clear tendon edge	F2 Blunt disruption with irregular tendon edge	F3 Disruption edge away from the amputated site > 2cm	F4 Disruption from MT junction*; Segmental tendon injury or loss
Artery	A1 Sharp cut	A2 Avulsed disruption < 10mm	A3 Avulsed disruption > 10mm; ribbon sign; red line sign,	A4 Segmental injury with or without artery loss
Nerve	N1 Sharp cut	N2 Avulsed disruption < 10mm	N3 Avulsed disruption > 10mm	N4 Segmental injury with or without nerve loss
Vein	V1 Sharp cut with sizable vein	V2 Avulsed disruption < 10mm	V3 Avulsed disruption > 10mm	V4 Segmental injury with or without vein loss; No sizable vein
Skin	S1 Sharp cut without laceration beyond the edge, No ecchymosis	S2 Jagged skin edges; Few ecchymosis or lacerations	S3 Ecchymosis or lacerations > 30% surface area of the amputated part	S4 Ecchymosis or lacerations > 60% surface area of the amputated part; Significant skin loss

* MT junction: musculotendinous junction

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APPENDIX -- Publications

1. Yu YC, **Huang HF**, Lin YH, Tseng YY, Yeong EK, Chen MT. Treatment Cost Analysis of Acute Burn Injury. The Journal of Taiwan Society of Plastic Surgery. 2013 Sep;22(3):188-198.
2. **Huang HF**, Yeong EK. Surgical treatment of distal digit amputation: success in distal digit replantation is not dependent on venous anastomosis. Plast Reconstr Surg. 2015 Jan;135(1):174-178. doi: 10.1097/PRS.0000000000000796. PMID: 25539304.
3. Wu YF, **Huang HF**, Liu TJ, Chang CW, Chuang SY, Yeong EK, Tai HC. Sepsis and Acute Acalculous Cholecystitis in Association with Major Burn - A Case Report. The Journal of Taiwan Society of Plastic Surgery. 2017 Mar;26(1):117-123.
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APPENDIX -- Patent

中華民國專利證書

發明第 I768990 號

發明名稱：可斷線的持針器

專利權人：黃慧夫

發明人：黃慧夫、張軒棠

專利權期間：自2022年6月21日至2041年6月27日止

上開發明業經專利權人依專利法之規定取得專利權

經濟部智慧財產局 局長 洪淑敏

中華民國 111 年 6 月 21 日

注意：專利權人未依法繳納年費者，其專利權自原繳費期限屆滿後消滅。

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