As techniques have improved, primary repair of flexor tendon lacerations, including zone II injuries, have become more common. Secondary reconstruction, whether in 1 or 2 stages, remains an important and useful technique for the treatment of these injuries. Current indications and methods, including delayed treatment and 1-stage and 2-stage reconstruction, are reviewed. Future directions of tendon reconstruction are also discussed. (J Hand Surg 2007;32A:1436-1442. Copyright © 2007 by the American Society for Surgery of the Hand.)

Key words: Flexor tendon, secondary reconstruction, zone II, tendon graft, Hunter rod.

Flexor tendon injuries account for less than 1% of all hand injuries; however, their effect on function for both the patient and society should not be underestimated. Primary or delayed primary repair of flexor tendon injuries, with changes in technique, rehabilitation, and technology, has moved to the forefront of treatment options. Secondary reconstruction, however, long the mainstay of treatment for these injuries, remains an important technique in the care of certain injuries.

Secondary reconstruction of tendon injuries in zone II (also known as “no man’s land”) using a silicone implant was first described by Bassett and Carroll in 1963 and refined by Hunter in 1971. Until the late 1970s, this type of 2-stage reconstruction was the standard for treatment of flexor tendon injuries in the finger. The use of a locally pedicled intrasynovial graft, flexor digitorum superficialis (FDS), instead of a more remote tendon has also been described. As results with primary tendon repair have improved, secondary reconstruction is mainly reserved for complicated injuries (Boyes grades 2–5, Table 1), or those that have failed primary repair.

Delayed Repair

In certain cases, primary repair can still be accomplished after a delayed presentation. This includes patients with missed injuries or those with associated medical conditions that have delayed surgical treatment. Substantial soft tissue or crush injury, infection, or soft tissue defects that may delay early rehabilitation may be contraindications for primary repair. Leddy type I avulsions involve retraction of the flexor digitorum profundus (FDP) tendon into the palm, with severe injury to the vascularity of the tendon and formation of a hematoma in the tendon sheath. These injuries are best treated early, before myostatic shortening occurs. In cases in which a delay is unavoidable, several options are possible. The tendon can be reconstructed as will be discussed later, the distal interphalangeal joint can be fused, or if functional, the finger can be left alone. In patients with Leddy type II or III avulsion injuries of the FDP in which retraction and myostatic shortening does not occur, primary repair can be delayed past 6 weeks. Ultrasound or magnetic resonance imaging, in addition to clinical examination, can be used to identify retraction of the tendon stump.

One Versus Two Stages; Making the Decision in Zone II

Patients who present either in a delayed fashion or who have segmental tendon loss are unable to be adequately treated with primary repair. In these patients, the decision needs to be made whether to reconstruct the flexor tendons in a single setting or to perform a 2-stage repair. In a single-stage reconstruction, the injured portions of tendon are removed and replaced with an appropriately harvested free tendon graft.

Both preoperative and intraoperative assessment is necessary for a successful outcome. Indications for a single-stage grafting procedure have been described by Pulvertaft and others. These include beginning...
with a hand or finger that has adequate passive motion of all joints, a well healed wound without excessive scarring, and a neurovascularly intact digit. Some loss of passive motion can be addressed with preoperative therapy. The patient must also be able to cooperate with a complex rehabilitation program. This precludes performing the procedure on children under the age of 3 years.\(^\text{11}\) The procedure may also have to be abandoned in favor of 2-stage reconstruction when intraoperative assessment demonstrates an inordinate amount of scarring in the surgical bed or an inadequate pulley system.

### Single-Stage Reconstruction

As described by Bunnell, strict surgical technique must be followed to obtain satisfactory results.\(^\text{12}\) This includes aseptic, bloodless technique and the preservation of the pulley system. The decision of whether to use a midlateral or zigzag (Bruner) approach is based partly on surgeon preference and partly on the presence of preexisting surgical or traumatic scar location.\(^\text{13}\) Some authors have suggested that using a midlateral incision keeps the scar from sitting directly on the tendon sheath. Care should be taken to ensure the preservation of as much of the tendon sheath and pulley system as possible. Originally it was recommended that only portions of the annular pulleys be retained, but current recommendations include preserving as much of the sheath as possible.\(^\text{14,15}\)

Donor tendons can be chosen from a variety of sources. This choice will be discussed in detail later; however, the most commonly used are ipsilateral palmaris longus tendon or plantaris. The use of plantaris tendon has the added benefit of additional length if needed.

Distally, the tendon is fixed to bone at the FDP insertion using standard techniques that have been well described (Fig. 1). If the stump of the FDP is long enough, the graft can be woven through for added fixation. Proximally, the graft may be fixed to the FDP tendon in the palm, just distal to the lumbrical insertion, if there is no scarring present. This is usually accomplished with a tendon weave (Fig. 2). The original tendon end should be prepared to remove any scarred, bulbous, or frayed tissue. As always, care must be taken to tension the graft appropriately. The profundus tendon can be grafted in cases of an intact and functioning

### Table 1. Boyes Classification

<table>
<thead>
<tr>
<th>Grade</th>
<th>Condition</th>
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<tbody>
<tr>
<td>1</td>
<td>Good. Minimal scar</td>
</tr>
<tr>
<td>2</td>
<td>Cicatrix. Deep scarring due to injury or prior surgery or infection. Loss of motion due to scar rather than joint injury</td>
</tr>
<tr>
<td>3</td>
<td>Injury to the joint resulting in loss of motion</td>
</tr>
<tr>
<td>4</td>
<td>Injury to the digital nerves</td>
</tr>
<tr>
<td>5</td>
<td>Multiple combined problems involving multiple digits, including one or more of the above categories</td>
</tr>
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</table>

Careful preoperative patient selection and discussion is necessary to ensure that the functional outcome after grafting is not worse than before surgery. Many patients do very well without a profundus tendon in the setting of a well-functioning FDS. Others have shown good outcomes with grafting through an intact FDS. Indications generally include skilled technicians or musicians, especially aged 10 to 21 years. A thin graft, such as plantaris, should be passed either through the FDS decussation or around it if too tight. An intact FDS should not be taken down in order to pass the graft.

With appropriate surgical technique and in a patient with the correct indications, single-stage grafting for flexor tendon injuries can result in excellent functional outcome. In cases with inadequate soft tissue coverage, dense scarring, or insufficient pulley systems, 2-stage flexor tendon reconstruction represents a better option.

Two-Stage Reconstruction

Once the decision to proceed with a staged reconstruction has been made, the soft tissues must be prepared for the eventual implantation of a final tendon graft. This involves several steps, including reconstruction of the pulley and sheath system, placement of a temporary implant, and guided rehabilitation to regain maximum flexibility prior to the second stage reimplantation. This method of flexor tendon reconstruction was first demonstrated by Hunter in 1965 and later refined in 1971.

Frequently a 2-stage reconstruction is selected because of inadequacy of the soft tissues, sheath, and pulley system. An adequate and functional pulley system is needed prior to implant of the temporary silicone graft. As was first described by Doyle and Blythe in 1975, the flexor tendon pulley system consists of annular pulleys A1 to A5 and cruciate pulleys C1 to C3. The most important pulleys, especially in reconstruction, are A2, located over the proximal phalanx, and A4, over the middle phalanx. At a minimum, A2 and A4 must be present or reconstructed to have a functional pulley system. The pulleys function to maximally convert tendon excursion efficiently into joint motion by preventing volar translation.

Several techniques are available for reconstruction of the pulleys. Intact but constricted pulleys can be dilated. Damaged but structurally sound pulleys can be directly repaired. The ideal graft for reconstruction of the pulley system would have an intrasynovial lining on the tendon gliding side. The reconstructed pulley must also be tensioned appropriately to perform its function properly while still allowing unimpeded tendon gliding. A free tendon graft can be used with a variety of suture techniques. The simplest is to use a remnant of free tendon graft. This encircles the phalanx and can be placed deep to the extensor mechanism. Originally, Bunnell described placing the graft deep to the extensors for reconstruction of A2 and superficial to the mechanism at A4; however, Taras and Kaufmann recommend placing the graft deep at all levels (Figs. 3A and B). Other more complex techniques include the Kleinert, Weibly, triple loop, Karev, and Lister techniques.
Some authors have suggested that the simple single-loop technique is too narrow to provide an adequate pulley. Okutusu’s triple-loop technique uses 3 passes of the graft around the phalanx and sutures. Kleinert’s technique was to weave a tendon graft through the old pulley rim. Karev’s “belt-loop” technique uses a portion of the volar plate as the pulley. Incisions are made distal and proximal in the volar plate, and the tendon is passed through. The inherent stiffness of the volar plate increases friction and inhibits gliding. Lister used a portion of extensor retinaculum, passing it around the phalanx. This provides an excellent surface for gliding at the expense of a second incision. Artificial materials have been used, including silicone sheet, Dacron graft, and polytetrafluoroethylene, but there is usually enough graft material to make the need for synthetics rare. In those cases in which artificial material is needed, polytetrafluoroethylene has been shown to be most attractive, as it is incorporated without foreign body reaction or adhesions.

Once the pulley system is reconstructed, the Dacron-reinforced silicone graft is passed. Distally, the implant is sutured below the FDP stump. Proximally no suture anastomosis is performed, allowing unimpeded gliding in the forearm or palm. Most important is ensuring that the implant glides smoothly and does not buckle with passive flexion.

After stage 1 of a flexor tendon reconstruction, it is vitally important to maintain or obtain full passive range of all joints. During rehabilitation, the goal is maximal passive motion and correction of contractures. Initially a dorsal blocking splint can be used with passive motion. Dynamic splinting can be used in cases of contracture release. Care must be taken in cases where nerve or vessel repair was performed, and postoperative rehabilitation will need to be adjusted accordingly. After allowing the scar to mature and wounds to heal, the second stage can be performed. Three months is generally agreed on as adequate time for the formation of a suitable gliding sheath around the implant.

The second stage involves the replacement of the silicone implant with a suitable tendon graft. Ideally, the pseudosheath is left intact, and small distal and proximal incisions are used to pass and secure the graft. Depending on which portions of the hand are scarred or involved, the graft can be fixed either in the palm or further proximal in the forearm. A motor unit must also be selected, and usually the adjacent profundus will suffice. If that is not suitable, the superficialis can also be used. The implant is detached from the distal stump, and the graft is sutured to the implant proximally, allowing it to be pulled through the proximal end of the sheath. The implant is removed and is passed within the sheath in a proximal to distal direction. The technique for fixing the graft distally is similar to that used in a single-stage reconstruction. Proximally, an interweave technique is used, ensuring appropriate tensioning of the graft.

Rehabilitation
Guided rehabilitation after both stage 1 and stage 2 in flexor tendon reconstruction is crucial to obtaining the best possible outcome. Over the last 20 years, early motion protocols have been developed. Several studies have demonstrated the efficacy of early motion on tendon gliding and healing of the repair. As suture techniques have improved, therapy protocols have become more aggressive. Rehabilitation after stage 1 involves mainly passive motion, attempting to gain maximum passive joint motion and improve contractures. This is typically begun several days after surgery. After stage 2, similar therapy is instituted. At rest, the hand is protected in a flexed position via splinting, and a passive motion protocol is begun. Others have recommended early active motion programs beginning as early as 2 weeks.
Choosing a Graft
A variety of options are available as suitable graft choices for the second stage of the reconstruction. The most obvious and easily available is the palmaris longus. This can be harvested from the ipsilateral forearm, if present, avoiding additional morbidity. In most cases where a tip to forearm graft is needed, the palmaris will be too short. Most frequently used in this instance is the plantaris. This of course requires access to the posterior medial heel for harvest. The plantaris tendon provides a graft long and thin enough for use in tip to forearm grafting. This tendon is present in approximately 80% of patients. Other less common sources may be used. These include harvest of toe flexors or long extensors, extensor indicis proprius and extensor digiti minimi. Up to 3 grafts may be obtained using the long toe extensors from the middle 3 toes. This graft is long enough for use in tip to forearm grafting. This tendon is present in approximately 80% of patients. Other less common sources may be used. These include harvest of toe flexors or long extensors, extensor indicis proprius and extensor digiti minimi. Up to 3 grafts may be obtained using the long toe extensors from the middle 3 toes. This graft is long enough for a complete graft but is usually larger than plantaris or palmaris, which can create problems in fitting the pseudosheath. The toe flexors to the second through fifth toes are intrasynovial grafts, potentially healing with fewer adhesions. These can be used in similar fashion to the toe extensors. Additionally, the extensor digiti minimi or extensor indicis proprius may be used. Either of these provides adequate length for palm to tip graft.

Zones III, IV, and V
Injuries involving the flexor tendons proximal to the tendon sheath may frequently be treated with primary repair. Reconstruction of a sheath and pulley system is not necessary in these zones. Patients with associated soft tissue defect, infection, or segmental loss may necessitate a more delayed form of reconstruction. In injuries involving zones III, IV, and V, several techniques have been used. This includes cases where the injury or repair is just underneath the A1 pulley and all or part of this pulley can be sacrificed. In delayed treatment where direct end-to-end repair is not possible, an interposition graft can be used as discussed earlier. Another option is end-to-side FDP transfer. The distal stump is sutured to an adjacent, intact FDP tendon. Also possible is the transfer of an adjacent FDS to the distal stump of the injured FDP.

Addressing Complications
Although it is a solution to a complex problem, staged reconstruction can be fraught with postoperative complications. Adhesions are the most common of complications. They can occur at graft junction sites or along the surface of the graft. A good postoperative therapy program helps to limit the formation of adhesions and can mobilize through some adhesions. If a plateau is reached despite appropriate therapy, tenolysis can be used to provide additional motion. This is especially true if passive motion is greater than active motion. Authors have suggested waiting at least 3 to 6 months following reconstruction before returning for tenolysis. Proper surgical technique will limit the formation of adhesions. Although less common, a reconstructed pulley may fail. This may be noted by decreased range of motion or bowstringing of the tendon. Either excessively aggressive rehabilitation or poor surgical technique may result in graft rupture. This can occur at both the distal and proximal junctures. Once again, strict adherence to appropriate surgical technique can limit this occurrence. If caught early, the graft may be salvaged by treating the rupture like an acute flexor tendon injury with early reoperation. As a salvage, an FDS finger can be created. The ultimate result with this treatment is a finger motored by a single FDS tendon with its insertion at the middle phalanx. The distal interphalangeal joint may need to be fused if unstable. Quadregia may also occur as a complication of improper tensioning or adhesions limiting excursion. Flexion of the adjacent digits will be limited as a result of sharing a common muscle belly when the repaired finger has reached maximal flexion. On the other extreme, a graft tensioned too loosely will result in a lumbrical-plus finger. Tension on the lumbral muscle will cause a hyperextension deformity of the interphalangeal joints. Hyperextension of the proximal interphalangeal joint may occur in hyper-lax patients who are missing an FDS tendon. Tenodesis of a slip of FDS may help prevent this complication. Complications may also occur after the first stage. Infection during this stage may ultimately necessitate removal of the silicone implant. Also possible is failure of the temporary implant. Leaving the proximal end free will limit the resulting proximal juncture failure and scarring; if it does not rupture at the proximal end, a distal rupture may ultimately result. Joint contractures may be noted early or late, and during rehabilitation after either the first or second stages. If caught early, a program of dynamic splinting can be initiated to achieve adequate motion. If this approach ultimately fails, surgical release can be performed. Synovitis is a problem that may also occur in patients after stage 1 reconstruction. This may result in impaired rehabilitation and a less optimized sheath for stage 2. Tight pulleys, poor implant gliding, or ruptures of the juncture of the implant may be pos-
sible causes. Ultimately, using appropriate surgical technique to ensure unimpeded implant motion and adequate distal fixation, as well as avoiding irritants such as talc, will help limit this complication. If the inflammatory cycle does begin, early treatment with temporary rest and splinting can assist in improving outcomes.

Difference in the Treatment of the Pediatric Population

Children with tendon lacerations pose a different clinical problem. While the tendons, sheath, and pulleys are structurally similar to those of adults, they are far more delicate. Pediatric patients are also difficult to examine. Up to 25% of patients may be undiagnosed at initial presentation. Primary repair in some cases can still be performed in children up to 2 months after injury with good results. In cases where primary repair is no longer feasible, grafting can be performed. This requires an intact sheath and pulley system and adequate proximal muscle excursion. Perhaps the biggest difference is in rehabilitation. This important phase of treatment requires the ability to actively understand and participate with the protocols as well as comply with treatment. As this is difficult to achieve in younger children, immobilization is used for 4 weeks. In older, more active children, a removable dorsal blocking splint can be used to prevent reinjury during daytime play. Two-stage reconstructions in children have been reported. Darlis et al used a modified Paneva-Holevich technique in 9 children with mostly good and excellent results. This involves a 2-stage reconstruction in which the FDS is sutured to the FDP proximal stump and then, in the second stage, is severed proximally and rotated as a pedicled graft. It is also important to keep in mind that excessive dissection around growth plates, transosseous tunnels and pulley reconstructions may result in growth disturbances.

Salvage

As mentioned previously, an FDS finger can be created, together with arthrodesis of the adjacent unstable joint, to provide an adequate functional result. Providing a finger with proximal interphalangeal motion alone motorized by a single FDS tendon may be advisable when the distal interphalangeal joint is unstable or unreconstructable. It may also be used as a salvage when distal pulleys are unable to be reconstructed or in cases of distal graft rupture after reconstruction. The staged reconstruction of flexor tendons in a badly injured extremity cannot be treated in an isolated manner without careful consideration given to the neurovascular status of the hand or finger. In many cases, amputation may give a better functional outcome rather than attempted replant or reconstruction. Indications for amputation or replantation are beyond the scope of this article but are nevertheless important in considering possible reconstruction.

Conclusions and the Future

Early repair of flexor tendon injuries, including those in zone II, has become a mainstay of treatment in these injuries. Delayed 2-stage reconstruction remains an excellent alternative to provide a functional digit in cases of failed early repair or when early repair simply is not an option. Strict adherence to surgical principles that have been established and access to appropriate hand therapy specialists can result in good outcomes for these patients. The last 30 years have seen tremendous strides in the understanding of the tendon biology of healing and repair. This has resulted in stronger repair techniques and improved therapy regimens with early motion protocols. Research, however, continues to attempt to find ways of improving healing and limiting adhesions and scarring. Current studies involve modifying healing at the cellular, molecular, and genetic levels. This includes the use of mesenchymal stem cells to speed or improve tendon healing or to provide tendon graft material. Work also continues on the use of molecular growth factors such as TGF-beta, PDGF, IGF, and BMPs to limit adhesion formation while promoting earlier healing. Similarly, research is looking at ways to use gene therapy to affect local mediator expression. None of these advances has made its way into current widespread clinical practice, but advancements in biologics may provide answers to today’s difficulties following flexor tendon reconstruction.

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