The resurgence of barbed suture and connecting devices for use in flexor tendon tenorrhaphy

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Abstract Barbed sutures and connecting devices have been historically described and used in flexor tendon tenorrhaphies. With the improvement in biomaterial, we have witnessed recently the resurgence of this concept. In this article, we review the historical use of barbed devices in repairing flexor tendons and explore the available barbed surgical devices that have been described in recent years.

Keywords Flexor tendon · Tenorrhaphy · Barbed suture · Anchoring device · Connecting device · Anastomosis

Introduction

Flexor tendon injury often results in disability, and many tenorrhaphies continue to fail [6, 7, 30, 31]. This motivated the continuous research for repair techniques, surgical material, and rehabilitation protocols to improve strength of repair site, decrease gapping of repairs, decrease gliding resistance of repaired tendons, enhance healing, and prevent adhesion formation [4, 5, 14, 23–25, 32–34, 44–46].

The most commonly used surgical material in tenorrhaphy is the use of suture material that requires knots. Increasing the number of strands crossing the repair site and use of epitendinous repair are well-recognized techniques that increase the strength of the repair site [15, 22, 37, 39]. However, the multiple strands repair techniques jeopardize the repaired tendon ability to glide leading to adhesion formation [41, 43].

The revival of barbed sutures and anchoring devices in flexor tendon repair has been recently reported [8–10, 26, 28, 38]. Barbed suture and flexor tendon repair devices remain less studied compared to the traditional suture counterpart. In concept, these devices have in common a holding capacity to the tendon tissues and do not rely on a knot for holding the repair intact as in the traditional suturing methods.

History of Barbed Sutures and Anchoring Devices in Tenorrhaphies

Anastomotic Device—McKee 1945

McKee, in 1945, described an anastomotic device to approximate tendon ends consisting of a metal tubes with small metal projections pointing toward the center of the tube. In the same article, he described the use of another anastomotic device that had holes and suture was passed through the holes to hold the tendon ends. This required a two-stage surgery for the removal of the tube. The rationale behind using a tube that encases the tendon was to decrease the amount of adhesions and have the barbs hold the tendon ends together. There was high rate of adhesion formation and functional limitation in the six patients who were treated with a combination of the two described devices [18]. This led McKee to propose a modified design with smaller “kick-ups” in the tube with a less bulky design Fig. 1. We were not able to find further accounts on the use of this modified tool.

Lengemann Barbed Wire Suture—Lengemann 1950

In 1950, Dr. Lengemann, an Austrian physician, introduced a new type of pull-out barbed wire suture for tendon

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Fig. 1 Image depicting the proposed anastomotic device described by McKee in 1945. Notice the “kick-ups” pointing toward the center of the tube. No suture is required for this device. A second surgery is required to remove the device and associated adhesions [18] (image redrawn using computer software)

surgery [16]. This suture consisted of a braided tantalum wire with a Weldon curved needle at the proximal end and a Weldon straight cutting needle at the distal end. It had a small Weldon semi-flexible V-shaped barb that was anchored on the surface of the tendon and acted to hold the tendon ends together. The barb prongs pointed toward the distal end of the suture. Suture ends were maintained on the surface of the skin after tendon repair was completed and fixed to the skin by means of two soft lead buttons until the healing process was complete. At the time of complete healing, the suture along with the barb was pulled out of the tendon and skin (Fig. 2)

This suture was introduced in the USA by Dr. Jennings [11–13]; the suture became erroneously known as Jennings suture instead of Dr. Lengemann, its inventor (Fig. 2). In 1955, Jennings reported his clinical experience with 30 flexor tendon repairs. The results were graded as good, fair, and poor by criteria described by Dr. Jennings in the article. Twenty-two tendons were repaired within the flexor sheath, and 45% of the repaired tendons had good results; in comparison, 100% of the eight tendons repaired outside the flexor sheath had good results. A good result was defined if the point of maximum function can be reached or approached to within a distance of 1 in. In speaking of flexor tendons, the ideal would be for the tips of the fingers to reach the distal palmar crease and for the tip of the thumb to touch the head of the fifth metacarpal. Jennings reported no infections with this technique and sensed the need for improvement when this tool was used for zone II repairs.

The technique seemed to be an attractive option, as it simplified the repair process and used a new concept. Surgeons in France, including Allieu, Rezvani, Foucher, and others, have used the same suture in repairing zone I and II flexor tendon injuries [2, 17, 27]. Marin Braun and Foucher in 1991 felt that barbed wire suture gave them poor results in repairing flexor tendons in zone II injury and abandoned the technique altogether. Instead, they used it to repair 77 flexor

tendon lesions in zone 1 via a rope down technique. This included 20 cases of repair of FPL. The patients were reviewed with an average follow-up of 4 years, and they found that immediate active mobilization was possible in 70 of the 77 cases. Mobility of the metacarpal (MCPJ) and proximal interphalangeal joints (PIPJ) were maintained in all but one case. Complications were noted in 12 patients out of the 77 cases; this included two ruptures of the barbwire, two minor infections and five major infections, two cases of adhesion requiring tenolysis, two cases of partial nail bed necrosis, one a patient with a flexion contracture of the PIP joint requiring arthrolysis, and one patient with reflex sympathetic dystrophy. Average time off work was 6.9 weeks (0–6 months). In conclusion, the surgeons found barbwire suture to demand meticulous surgical technique and close postoperative surveillance.

Bunnell's Gig Pull-Out Suture 1954

Dr. Sterling Bunnell proposed the use of an anchoring device, which he called the gig pull-out suture based on the principle of the gig on a spear for catching fish [3]. This is a similar

Fig. 2 Image showing the use of Lengemann, also known as Jennings barbed wire suture for repairing flexor digitorum profundus tendon in the palm. Notice the use of lead buttons to attach the wire on the surface of the skin. Device was pulled out after healing was complete [13] (image redrawn using computer software)

design to Lengemann's barbwire suture and consisted on a gig that acted as an anchor instead of the semiflexible barb used in Lengemann's [3]. Bunnell developed it to speed up and simplify the suturing of tendons. He found it useful in extensive primary repairs, in inserting tendon into bone, and, at times, for tendon suture other than at insertion. It holds the tendon distally until the tendon unties; it is then withdrawn. The concept of this suture and the way it was used are very similar to the Lengemann suture. No other article was found describing its use.

Barbed Suture—McKenzie 1967

In 1967, McKenzie from New Zealand described the first account for the use of an internal multiple barbed suture for repairing tendons of the palm and finger [19, 20]. It was made of nylon and had numerous small barbs. This suture was found in two forms; form A had unidirectional barbs, and both ends of the suture were kept on the surface of the skin and was removed after 4 weeks. The other form, form B, was a nylon suture that had numerous barbs arranged in two opposing groups; each group had its barbs pointing toward the center of the suture and away from the two straight needles attached at either end of the suture. The second form was intended to remain in situ after repairing a tendon (Fig. 3). For complete tendon lacerations and for

Fig. 3 McKenzie proposed multiple configurations for the use of his barbed suture. Unidirectional sutures had to be anchored on the surface of the skin, whereas bi-directional sutures were used within the tendon. Unidirectional sutures were pulled out after healing was complete [20] (image redrawn using computer software)

tendon transfers, the need for two suture materials was described. This suture was not used in patients. A patent registered by Alcamo seems to be the first documented example of barbed suture material up to our knowledge. Nevertheless, use in tendon surgery was not described specifically in his patent (Fig. 4) [1].

Unidirectional and Bidirectional Barbed Suture—Shaw 1968

In 1968, Peter C. Shaw from Guy's Hospital in London described the use of a barbed wire suture, which consisted of a braided wire suture that had a straight cutting needle at each end [29]. At the center of the wire are two sets of four metal barbs facing opposite directions, each set having its barbs pointing away from the needle to its end. Each set of barbs occupied 25 mm at the center of the suture and 3 mm separated the two sets of barbs. He used a tendon clamp to hold the end of the transected tendon in order to minimize trauma to the surface of the tendon hoping to decrease adhesion formation. This suture was used in cadaveric human profundus tendon and in a series of operations on a canine model. Testing indicated that the barbed suture has a better grip on tendon than the standard wire used at that time. Experiments on dogs gave poor results [29]. In addition, he described the use of this suture in zone II tendons in patients; his method requires exposure of 2.5 cm of the lacerated tendon on each end to accommodate the barbed segment in the suture. This is considered to be excessive in today's standards. The suture ends were then passed outside the skin and cut flush. Patients were immobilized for 3 weeks. Use was limited to two patients, one of whom had a repair in zone II; this patient had a range of motion of the MCPJ of 20–80°, PIPJ of 50–80°, and DIPJ of 20–45° of the little finger. The surgeon admitted inability to make any final conclusions. There was no further testing reported on other patients using this suture.

Although several examples of barbed suture and connecting devices were historically introduced to treat flexor tendons of the hand, none of these older methods survived in the current hand surgery practice. In addition, many of the technical comments mentioned in these articles were the state of the art in tendon surgery in that era but no longer apply to today's practice. Improvement in biomaterials, rehabilitation protocol, and in our understanding of the basic science of tendon healing might have been the reason for reconsideration of similar devices in our days.

The Revival of Barbed Sutures and Anchoring Devices

Teno Fix™

Recently, the Teno Fix™ device has been described and used for zone II flexor tendon repair [28, 35, 36]. The

Fig. 4 Multiple configurations of barbed sutures as described by Alcamo. No report of use of this suture in tendon repair was found [1] (no permission required according to the US Patent and Trademark Office)

March 3, 1964

J. H. ALCAMO
SURGICAL SUTURE

3,123,077

Original Filed Aug. 13, 1956

2 Sheets-Sheet 1

Teno Fix device is composed of two intra-tendinous, stainless steel anchors joined by a single multifilament 2-0 stainless steel suture. Each anchor is 2.2 mm in diameter and 4.0 mm in length, and the suture is 0.3 mm in diameter.

This device was shown to withstand significantly greater force and energy at a 2-mm gap than does a 4-0 four-stranded cruciate repair in a canine model [35]. This is in contrast to a study performed by Wolfe et al.; they studied the mechanical behavior of Teno Fix repairs compared to

cruciate and modified Kessler repairs and found that there was no significant difference in displacement between the cruciate, modified Kessler, and Teno Fix repairs. The cruciate repair had greater resistance to gap formation and repair-site failure when compared with the Kessler and Teno Fix repairs. No significant difference was found between the modified Kessler repair and the Teno Fix repair [40].

Subsequently, a randomized, multicenter, blinded, clinical trial was carried out on 67 patients with isolated zone II flexor tendon injury. There were 85 injured digits: 34 were treated with the Teno Fix, and 51 served as controls. A modified Kleinert rehabilitation protocol was employed, with active flexion starting at 4 weeks postoperatively. Patients were observed for 6 months by blinded observers who assessed the patients' outcomes using the Disabilities of the Arm, Shoulder, and Hand (DASH) score and other clinical criteria. Results showed that none of the Teno Fix repairs ruptured, and nine of the 51 suture repairs ruptured ($p < 0.01$). There were no differences between the two groups in terms of DASH score and other clinical parameters. One Teno Fix device migrated and extruded secondary to a wound infection.

Of the 85 tendons repaired 4.7% were found to be too small for the device, and in 10.6% of the tendons, the exposure was not sufficient. The authors concluded that Teno Fix is a safe and effective method for tendon repair with similar functional outcomes and lower rupture rates, especially in patients who are noncompliant with the rehabilitation protocol [36].

More recently, Rochhi et al. report on their experience in treating 21 patients presenting primary flexor tendon injuries within the digital sheath in zone II. There were, according to Strickland and Glogovac criteria, 12 excellent, six good, and three fair results. The authors' conclusion was that Teno Fix can produce strong tendon repairs, but the best indication is to treat selected cases of sharp flexor tendon injuries in zone II [28].

New Anchoring Device—Hirpara 2010

More recently, Hirpara et al. used a nitinol device with barbs, created by making a pattern around the length of a nitinol tubing as an anchor for tendon repair (Fig. 5). Nitinol is a flexible alloy of nickel and titanium. Double-ended suture was attached to enable easy insertion into the tendon undergoing repair. The length of the device enabled the use of at least 10 mm of each divided tendon end for repair. Each barbed section was 12 mm long; the device diameter is 3 mm, and this allowed the investigator the use of two devices in one repair. The repair technique included inserting the device using a needle into one of the ends of the divided tendon and passed along its length for 20 mm. The suture was pulled through until the other half of the

barbed tube reaches the stump end, and the process was repeated for the other end. The authors described that they faced significant resistance while applying the device.

The investigators studied five groups of 20 porcine tendons repairs. Three groups were repaired using the Pennington-modified Kessler technique, the cruciate, or the Savage technique, one using one nitinol device per tendon and the other with two nitinol devices per tendon. Half of the tendons received supplemental circumferential Silfverskiöld type B cross-stitch. The repairs were loaded to failure, and a record was made of their bulk, the force required to produce a 3-mm gap, the maximum force applied before failure, and the stiffness. When only one device was used, repairs were equivalent to the Pennington-modified Kessler for all parameters except the force to produce a 3-mm gap when supplemented with a circumferential repair, which was equivalent to the cruciate repair. When two devices were used, the repair strength was equivalent to the cruciate repair, and when the two-device repair was supplemented with a circumferential suture, the force to produce a 3-mm gap was equivalent to that of the Savage six-strand technique [8]. Similar to other repair techniques using anchoring devices, the authors cite the ease of the device use and the simplicity of the technique as advantages. There was no testing for the gliding resistance in their repairs, and this barbed device was not used in any clinical trials as of the time of writing of this article.

Barbed Suture

Quill™

A Quill™ suture was introduced initially as a barbed monofilament suture made from polypropylene, nylon, and glycolic acid derivatives. The barbed segment in this suture is divided into two halves; this suture is a structure with polarity, and each side has its barbs oriented away from the needle on its side and in a spiral fashion. We find this description resembling that of McKenzie and Shaw's sutures described earlier. The mid-point of the barbed segment can be determined by looking for a segment that has no barbs or feeling for resistance once the other half of the barbs are passed through the tissue. The suture has two curved, diamond-pointed needles in the most commonly used form. This suture was first introduced in facial suspension procedures and commercialized under the name contour thread lift procedure. Other examples of sutures resembling this design include aptos or featherlift from Russia. More commonly, Quill is used in subdermal skin closure.

Quill has been recently utilized in cadaveric flexor tendon repair [26, 38]. In the study by Trocchia et al., the authors compared repairs performed in cadaveric tendons

Fig. 5 **a** Part of the schematic used to instruct the laser cutting machine during manufacture of the device. The image has been cropped to highlight the barbed portion. **b** The resultant profile formed when the schematic in **a** is wrapped around the length of the nitinol

tubing. The barbs are then lifted away from the surface of the device to allow engagement with the substance of the tendon after insertion [8] (image redrawn using computer software)

using either a 3–0 Ethibond with a Kessler repair or a 2–0 Quill sutures in a Kessler–Bunnell repair and were biomechanically tested. The mode of failure for the Ethibond sutures was suture pull-out two times and knot failure in 18 of 20 times, while the Quill sutures failed entirely by pull-out. Maximum load to failure was 34.7 ± 5.4 N and 29.6 ± 3.6 N for Ethibond and Quill, respectively. This was found to be statistically significant ($P=0.001$). Tensile load at 2-mm gapping was 22.8 ± 6.3 and 22.2 ± 4.0 N for Ethibond and Quill, respectively. No statistical significance was found ($P=0.723$).

Despite the longer working distance of 2.5 cm and suture length used with the Quill group, and despite the more technically demanding suturing technique used for Quill suture, Quill repairs had a lower strength compared to 3–0 Ethibond use in a modified Kessler technique. In addition, the number of passes of Quill outside the tendon means that there is more surface trauma to the tendon and potential for higher adhesion formation in vivo. A weakness in this study is that gliding resistance or work of friction testing was not performed to test how would the tendon act within the tendon sheath; this can be a critical factor especially given that the repair technique used included passing the suture on the surface of the tendon eight times on one end of the repair [22].

A second study exploring Quill suture in tenorrhaphies was done by Parikh et al. [26]; they randomized 38 cadaveric flexor digitorum profundus tendons into polypropylene-barbed suture repair in a knotless three- or six-strand configuration or to unbarbed four-strand cruciate repair. The authors compared the cross-sectional area before and after tenorrhaphy. Tendons were distracted to failure. No testing of gliding resistance was made. The mean cross-sectional area ratio of control repairs was 1.5 ± 0.3 , whereas that of three- and six-strand barbed repairs was 1.2 ± 0.2 ($P=0.009$) and 1.2 ± 0.1 ($P=0.005$), respectively. Mean load to failure of control repairs was 29 ± 7 N, whereas that of three- and six-strand barbed repairs were 36 ± 7 N ($P=0.32$) and 88 ± 4 N ($P<0.001$), respectively. All cruciate repairs failed by knot rupture or suture pull-out,

whereas barbed repairs failed by suture breakage in 13 of 14 repairs ($P<0.001$). In an ex vivo model of flexor tenorrhaphy, a three-strand barbed suture technique achieved tensile strength comparable to that of four-strand cruciate repairs and demonstrated significantly less repair-site bunching. A six-strand barbed suture technique demonstrated increased tensile strength compared with four-strand cruciate controls and significantly less repair-site bunching.

The three- and six-strand repairs described by the authors involved passing Quill suture outside the tendon 12 and 18 times, respectively. This again can increase surface damage to the epitenon and potentially increase adhesion formation [21, 23]; the authors argue that the barbs can be buried if the needle passes through the same hole. This, however, does not preclude that the suture might increase the gliding resistance and potentially cause further damage to the overlying epitenon during range of motion. The surgical techniques described seem to be tedious, and as mentioned above, there is a chance that suture might be cut while performing the repair. Decreased cross-sectional area that was noted does not automatically mean that gliding resistance would be decreased. In fact, the use of three and six sutures in the described configurations has the potential to increase the stiffness of the tendon at the repair site and adversely affect the gliding resistance [42]. This is an area that needs to be studied in further detail.

Depending on the suture configuration using more than one suture for the repair might increase the chance of cutting previously placed suture, compromising the repair.

The bidirectional nature of Quill may make it an unforgiving suture for repair after the suture ends are cut; removal of the suture might lead to compromise of intact tendon tissue. We feel that in order for bidirectional barbed suture to be usable in flexor tendon repair, it has to have better anchorage in the surrounding tissue to allow shorter working length, simpler repair, less exposure, and shorter suture length.

Ingle et al., in a finite element model, studied different configurations of barbs and the mechanical interaction with surrounding skin and tendon tissue with the goal to optimize suture function [9, 10]. The experimental results revealed that since the tendon tissue has a higher modulus than the skin, it needs a more rigid barb to penetrate and anchor the surrounding tissue. A cut angle of 150° and a cut depth of 0.18 mm are therefore recommended. On the other hand, for the softer skin tissue, a cut angle of 170° and a cut depth of 0.18 mm provide a more flexible barb that gives superior skin tissue anchoring. These findings confirm that the future development of barbed suture technology requires a detailed understanding of the biomechanical properties of the tissue in which they are to be used. This will lead to the future development of a range of tissue-specific barbed sutures.

V-Loc

Another form of barbed suture was introduced recently for surgical wound closure. This is a unidirectional barbed suture with a curved needle on one end and a loop of suture on the other end. This suture might be more challenging to utilize given that it relies on the looped end to achieve initial anchorage in tissue. It can potentially be used as a surface pull-out suture technique; however, this technique has generally run out of favor given the current state of art in flexor tendon repair.

Summary

The concept of barbed sutures and anchoring devices was abandoned by surgeons in the past and is revived today given the improvement of biomaterials and technology. We find that available devices may solve some problems we face in flexor tendon repair.

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