

Fascial Closure New Surgery Paradigms



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Keywords

• Suture • Mesh suture • Laparotomy closure • Foreign body reaction • Suture/tissue interface • Suture pull through • Suture tension • Primary mesh augmentation

Key points

- The ultimate tensile strength of newly apposed tissue is the sum of the strength of the physical construct holding the tissues and the strength of biologic healing.
- For successful laparotomy closure or incisional hernia repair, the total strength of the repair must remain greater than the opposing forces applied at the suture/tissue interface.
- Given limited progress over recent years, recent research focuses on an improved distribution of forces at the suture/tissue interface that can limit tissue tearing, suture pull-through, and incisional hernia formation.

INTRODUCTION

For decades, biologic wound healing was thought to be the main contributor to the strength of a fascial closure. More recently, an improved understanding of the physics of tissue apposition has yielded improved clinical outcomes for laparotomy closures. Given that laparotomy closure is important to many of the disciplines of surgery, including general surgery, plastic surgery, urology, and gynecology, it is imperative to understand the closure of the midline abdominal incision to limit incisional hernia formation—a clinical entity that leads to hundreds of thousands of surgeries and billions of dollars spent worldwide.

The oldest known suture was found in a mummy from 1100 BC in ancient Egypt [1]. At that time, sutures were made of plant materials such as flax, hemp, and cotton or animal material ranging from hair, tendons, arteries,

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muscle strips and nerves, silk, and catgut. The commonality of all these designs both old and new is that sutures are flexible linear elements that are passed through tissues to approximate tissues. Tension across the suture line is maintained with a surgically created self-holding knot. The tension achieved by the suture results in a localized ischemia within the loop of suture, inflammation, and the beginning of the wound healing cascade. Simultaneously, the tissues react to the suture in a foreign body reaction, where the body encapsulates the suture and any secondary suture degradation products.

When 2 tissues edges are approximated, the total force experienced on each suture is the sum of these forces, plus an additional amount of force that actually compresses the 2 edges together along the suture line. The diameter of the suture plays a role at each suture/tissue interface (STI), because the local tension that is experienced is the force divided by the surface area of contact. This concept is important when it comes to suture choice, because fine sutures concentrate forces at the STI, whereas larger sutures are able to distribute and lower the forces at these points, thus working to avoid suture pull-through. When the tissue's ability to withstand the outward force is less than the forces at the STI, suture pull-through or cheese-wiring occurs. It is this process that ultimately can lead to an abrupt acute dehiscence.

In the "fourth dimension" of time, permanent sutures can slowly pull-through the tissues, leading to the commonly described Swiss cheese hernia. The hallmark of these conditions is loose permanent sutures that can be pulled away from the abdominal fascia (Figs. 1 and 2). The scar tissue found within the multiple loops of suture remodels in response to tensile and extensile forces of the abdominal wall and thins. After many years, a steady state results that is either strong enough to maintain the viscera (success), or is unable to contain the viscera and results in an incisional hernia. The quality of the laparotomy closure is determined by its weakest spot, as even a single localized area of incompetent scar will be categorized as a surgical failure.

WOUND HEALING, INFLAMMATORY RESPONSE TO BIOMATERIALS, AND THE FOREIGN BODY REACTION

The inflammatory phase of wound healing is initiated by the tension at the STI owing to ischemia by the loop of suture [2]. Initially, the tissues become inflamed with the accumulation of neutrophils within the wound bed. A porcine laparotomy model revealed a 25% decrease in suture tension only 30 minutes after fascial closure, which progressed to a 50% decrease by 23 hours [3]. The phenomenon of tissue creep and stress relaxation, whereby tissues placed under tension elongate over time, occurs independently. Inflammation of tissue within the suture loop weakens the tissue either by the release of collagenases or by neutrophil-mediated mechanisms [4], further facilitating the failure of the physical construct at the STI [5]. This initial weakening of the physical construct can be visualized and was first demonstrated in the initial downward strength curve of a repaired dog tendon published in 1941 by hand surgeons at Northwestern [4].



Fig. 1. A porcine laparotomy model showing a loose suture that can be pulled away from the fascia 3 months after implantation. If the monofilament suture was placed with enough tension to appose the tissues initially, the only explanation to explain this looseness is suture pull-through.

The proliferative or granulation phase represents the second phase in wound healing and is present in the background, but does not start to accelerate until days 5 to 14. This stage involves the laying down the framework of new collagen and glycosaminoglycans by fibroblasts. This combination of proteoglycans is the key step to providing the initial stability to the wound. The process of neovascularization also occurs during this time period, where bud formation of blood vessels and creation of the extracellular matrix and fibronectin come together. Leading up to the third and final phase, there is continued deposition of fibroblasts and myofibroblasts. The maturational or remodeling phase starts around day 14 onwards and can last up to years. During this phase, cross-linking of collagen fibers along with deposition of additional fibrous tissue occurs.

The immediate host response to any implanted material is characterized by nonspecific protein adsorption, fibrinogen deposition, formation of a blood-derived provisional matrix, and recruitment and activation of inflammatory cells [6]. Although polymer surface chemistry certainly affects the interfacial dynamics of plasma protein adsorption, Brash and Lyman (1969) found that plasma protein behavior varies insignificantly on a variety of hydrophobic surfaces. [7,8].

Barring infection, acute inflammation subsides and is replaced by a state of chronic inflammation, which lasts for the life of the implant. Chronic inflammation may be variable, but the hallmark of the chronic foreign body reaction



Fig. 2. Another porcine abdominal wall section showing hallmark findings of loose permanent sutures that can be pulled away from the abdominal fascia 3 months after implantation.

(FBR) is the coalescence of monocytes, macrophages, and foreign body giant cells at the STI. The process of frustrated phagocytosis as termed by Henson in 1971, occurs as the foreign body giant cells attempt to phagocytose the foreign biomaterial, concurrently releasing reactive oxygen species and matrix metalloproteinases and their inhibitors [8]. Finally, within 1 to 3 weeks, the chronic inflammatory interface, made up of a layer of foreign body giant cells and a few layers of monocytes, is surrounded by extracellular matrix deposition and granuloma. Once the foreign body granulomata have formed, the chronic lifelong inflammation is independent of biomaterial composition. It is at this stage where the foreign body has essentially been walled off. In large-pore materials with individual filaments more than 1 mm from each other, normal fibroblast infiltration and collagen deposition are allowed within the spaces between granulomata surrounding individual mesh fibers, and this is a more biocompatible process, termed incorporation. In small-pore materials, the granulomata abut one another and form bridging scar [9]. The material is “encapsulated,” a process that is associated with excess collagen fibers aligned parallel to the implant surface [10], contracture and wrinkling of deformable implants, loss of appropriate implant function, and possibly pain.

Absorbable suture materials aim to avoid long-term sequelae of the FBR such as chronic inflammation, pain, or late infection by disappearing over time. The purpose of absorbable sutures in theory is to provide a temporary structural support at the STI, giving the body time to heal until the suture is no longer necessary. Absorbable sutures initiate a robust and relatively transient inflammatory response when compared with nonabsorbable materials. Additionally, the literature suggests that with the passage of time an absorbable implant will dissolve and the FBR will come to an end. Delbeke and colleagues [11] (1983) found nearly no evidence of tissue reaction about residual polydioxanone suture compared with a moderate but persistent histiocytic response to polypropylene at 80 days after implantation. Moreover, other studies have demonstrated that explantation of a permanent foreign body results in resolution of frustrated phagocytosis and the disappearance of FBR. Thomson [12] demonstrated in the 1970s that the capsule or pseudosheath around a foreign body does not persist in the absence of the foreign body. This process in turn leads to a static scar, void of an FBR. As discussed elsewhere in this article, scar remodels and thins over time in response to tissue forces. Therefore, for newly apposed tissues that requires a permanent and strong hold, such as for laparotomy closure, there is a theoretic need for a nonabsorbable material with large pores and small filaments that has the ability to incite a mild to moderate well-sustained dynamic FBR and a scar that does not weaken over time.

STRENGTH OF TISSUES REPAIRED WITH SUTURES

The total integrity of the physical construct along a suture line is composed of a multitude of factors, including the number of “grabbing points” that the suture makes with the tissue, the tensile strength of the suture, the ischemia along the wound edge by these sutures, the strength of the tissue itself, the ability of the collagen fibers within the tissue to resist suture pull-through, and the strength of the knot. It has also been observed that sutures tend to break at the knot rather than at any point along its length. Placing additional sutures along an already established suture line may increase the overall construct strength; however, this addition is at the expense of adding to tissue ischemia at the wound edge, which can overall compromise wound healing.

SUTURE COMPOSITION

Historically, sutures have been made of natural fibers derived from plants (eg, cotton, linen, tree bark), cattle intestines (catgut), animal or human hair, metal wires (eg, iron, gold, silver), silk, and so on. Surgeons still use catgut, silk, and even human hair [13] nowadays. However, the natural sutures have been almost completely replaced by synthetic materials, either absorbable (eg, polyglycolic acid, polyglactin 910, poliglecaprone 25, polydioxanone) or nonabsorbable (eg, polypropylene, polyamide, polyester, steel) [14]. Most synthetic hernia meshes are composed of relatively inert biomaterials, such as polypropylene, polytetrafluoroethylene and polyethylene terephthalate. Polypropylene is characterized by an intense early FBR with late resolution. It induces more

collagen deposition than expanded polytetrafluoroethylene [15]. Polypropylene is a nonabsorbable filament with a long history of medical use since the 1950s [16]. Published accounts show safety of its long-term use, even in neonates and infants [17,18]. Also, in regard to knot security, the low tissue reactivity and the ease of passage of monofilament polypropylene through tissues is due to its low friction, and low friction sutures have little to prevent untying of knots [19].

SUTURE TENSION

Suture adds an element of injury or reactive inflammation during the approximation of otherwise nonwounded tissues. Supporting the concept that stitches are the main inducer of scar is the finding that 5-hydroxyproline (correlating with scar strength) is greater around the suture than in the interstitch zone. Animal-based evidence has shown that there is an optimal amount of tissue injury required for the initiation of healing [20]. Minimally wounded tissue edges and low suture tension is associated with lower burst strength than the approximation of gently wounded tissue edges with appropriately tied sutures. Tissues approximated by tightly tied sutures also have measurably less perfusion [21] and decreased burst strength, implying that the suture tension curve is parabolic with an ideal approximation force. The optimal approximation force is difficult to obtain, because it is challenging to judge the tension applied on to a suture, even for experts [22]. For this reason, engineers have fabricated suture tension sensors for use in the operating theater to provide immediate feedback to the surgeon. With running closures of the abdominal wall, placement of the fifth, sixth, and seventh stitches no longer influences the force experienced at the second throw. In a continuous suture, the tension thread in the filament remains constant only 3 loops away from the pulled loose end of the suture. Therefore, for a single incision, there can coexist areas of elevated and depressed tension that can cause changes to the quality of the closure and subsequent wound healing [23].

SUTURE SIZE

The effect of suture size on suture pull-through has been studied, although the data are not conclusive. Campbell and colleagues [24] determined using a human cadaver autopsy model that there was no significant relationship between pullout strength and suture size. One can see from the data that the diameter of the suture increased from 0.3 mm to 0.5 mm for these experiments, but the mean pullout force varied around 50 N (Fig. 3).

More recently, Cooney and colleagues [25] managed to identify only a weak relationship between the pullout strength required to tear suture through both human and porcine abdominal walls with a marginally significant difference identified between the thinnest (PDS 2-0) and the thickest (PDS 1) sutures examined (Figs. 4 and 5). They concluded that “choice of suture size appears to only significantly affect suture retention if the difference in suture diameter is greater than or equal to 0.1 mm.”

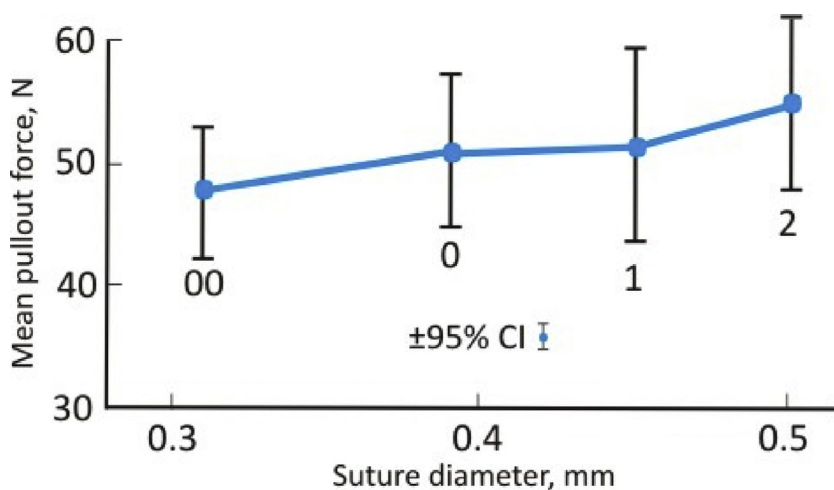


Fig. 3. Relationship of suture diameter and pullout force. CI, confidence interval. (Adapted from Campbell JA, Temple WJ, Frank CB, Huchcroft SA. A biomechanical study of suture pull-out in linea alba. *Surgery*. 1989;106:888-92; with permission.)

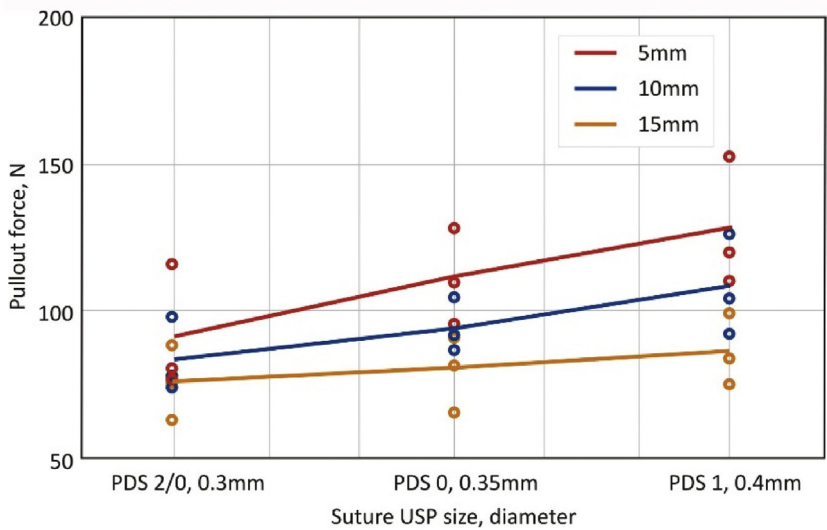
NEW OPTIONS FOR FASCIAL CLOSURE TO DECREASE HERNIA RECURRENCE

Minimal strides have been made in the laparotomy or hernia repair field along with a failure rate of suture repairs of incisional hernias of 63% at 10 years [26] and perhaps explained by a reliance on the standard suture design for tissue approximation. Translating concepts of the biology and physics involved at the STI has propagated a need for new, more reliable types of abdominal wall closure.

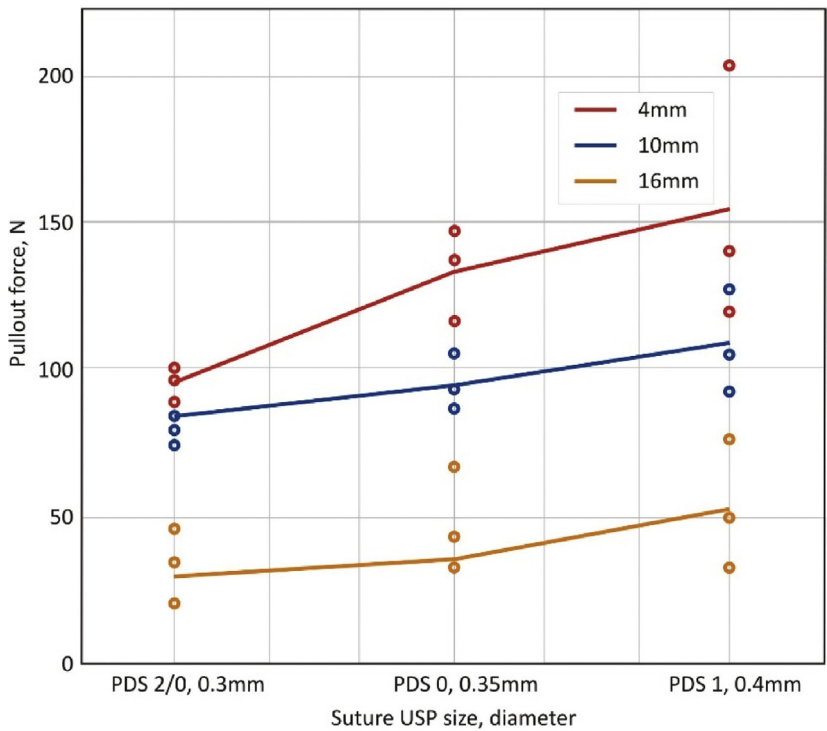
In terms of human clinical experience level one evidence exists from the STITCH trial that, for thin patients (average body mass index of 24 kg/m²) undergoing midline laparotomy, small bites 5 mm from the edge of the incised linea alba and spaced 5 mm from each other using a relatively small 2-0 polydioxanone suture resulted in fewer incisional hernias than the traditional 1-cm bites spaced 1 cm from each other with a number 1 polydioxanone suture [27]. A relatively high rate of incisional hernias were found in both arms of the study (small bites 13%, large bites 24%), although this rate was attributed to radiologic identification of small abdominal defects with routine ultrasound examination.

This study builds on prior clinical work that the working length of a running suture used to close a laparotomy incision should be more than 4 times the length of the incision it closes for the lowest hernia rate [28]. It should be noted that the small bite closures used more suture than the large bite closures, serving to better distribute forces and to increase the area of the STI. The small bite closures had double the gripping points to hold the tissue in apposition in

A



B



comparison with large bites, causing the force at the STI to be halved. However, 2-0 suture has a smaller diameter than a number 1 (0.35 mm vs 0.50 mm), that would serve to increase the force locally and increase the tendency to cheese wire. Overall, the increase in the construct strength achieved by the 2-0 small bite closure clinically was an improvement over the large bite number 1 closure. The current literature shows more effect with the placement of the sutures (small bites), more so than the size of suture (Campbell and colleagues, 1989 [24]; Cooney and colleagues, 2017 [25]).

PROPHYLACTIC MESH AUGMENTATION

Additionally, recent studies including the PRIMA trial have moved toward using a combined technique, with both sutures and mesh to achieve a lasting abdominal wall closure in higher risk patients who are defined as those with a body mass index of more than 27, or undergoing open abdominal aortic aneurysm repair [29]. Termed primary mesh augmentation, the mesh is placed prophylactically to distribute forces and to limit tearing at the STI. The mesh serves to add additional foreign body reaction scar around the filaments of the mesh to enhance construct strength and decrease overall hernia recurrence rate. However, this strategy is not without its drawbacks; the risk of seroma formation is greater in primary mesh augmentation compared with primary suture repair, in particular with onlay placement (18.1%) compared with primary suture (4.7%) and sublay mesh placement (7%). Importantly, the higher seroma rates did not translate into higher rates of surgical site infection, dehiscence, or reoperation. Overall, 5% of the meshes were removed during the clinical care of these patients, and this factor must be balanced against the decrease in incisional hernias from 30% (sutures only) to 13% to 18% (primary mesh augmentation groups). Similarly, the AIDA trial using a prophylactic onlay mesh at the time of abdominal aortic aneurysm repair decreased the 2-year incisional hernia rate from 23% to 4%, also at the cost of early problematic seromas [30]. Risk calculators of which patients are most likely to develop an incisional hernia will be critical to stratify who would most benefit from the extra work, dissection, and expense of a prophylactic mesh [31].

With regard to hernia repair with absorbable or partially absorbable mesh, the strength of the mesh must be replaced with durable scar to avoid hernia recurrence. In a sheep abdominal wall model, TIGR Matrix (Novus Scientific, Uppsala, Sweden) long-term resorbable mesh (glycolide-lactide-trimethylene carbonate copolymer knit with lactide-trimethylene carbonate copolymer) was associated with increasing collagen type I/III ratio for up to 24 months

Fig. 4. Pullout forces for 3 types of suture thickness. (A) For different bite separations; (B) For different bite depths. (*Adapted from* Cooney GM, Lake SP, Thompson DM et al. The suture pullout characteristics of human and porcine linea alba. *J Mech Behav Biomed Mater.* 2017;68:103-14; with permission.)

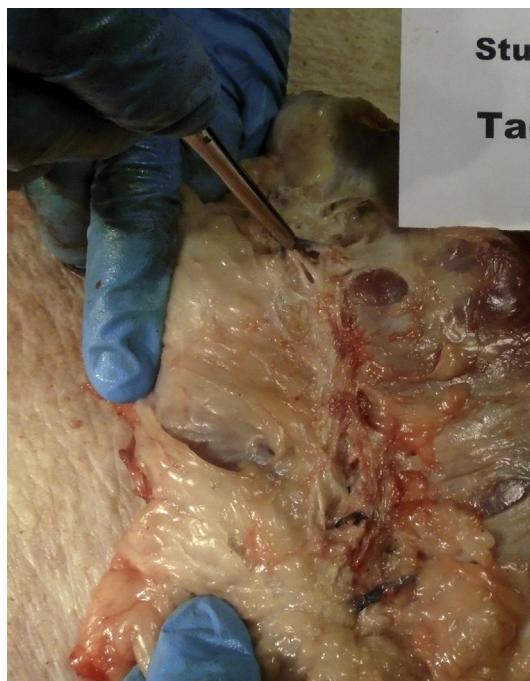


Fig. 5. A porcine laparotomy model exhibiting well-approximated mesh suture with no evidence of pull-through. The mesh suture has been incorporated by the tissues and so tension onto the suture by the visible pick-up shows it to be well fixed and resists being pulled away from the abdominal wall.

and full resorption at 36 months [32]. Phasix (Bard Davol, Warwick, RI) P₄HB monofilament mesh is another long-term resorbable mesh, with a near-total resorption period of 72 weeks. The ball burst strength of the P₄HB mesh in a porcine hernia model demonstrated maximum repair strength at 16 weeks, followed by a steady decrease through the study period of 72 weeks to a level equivalent to the strength of the native abdominal wall [33]. It remains unknown whether the repair strength would continue to decrease as the mesh completely degraded. Peeters and colleagues [34] (2013) compared primary repair with direct-supported repair with GORE BIO-A Tissue Reinforcement mesh (W. L. Gore & Associates, Flagstaff, AZ) (polyglycolic acid-trimethylene carbonate, 6 months near-total resorption) in a rabbit model. At 1-year after implantation, the GORE BIO-A Tissue Reinforcement mesh had completely degraded, there was no residual inflammatory reaction, and the mesh-supported repair had a similar collagen profile to primary repair. Although neither group experienced recurrence, the tensile strength of the bio-absorbable mesh-supported repair was statistically similar to primary repair (18.7 vs 25 N/m, respectively) [34]. Based on the available evidence, the

FBR resolves when the foreign body is absorbed or removed. For hernias, where the prevention of recurrence depends on the final combined strength of prosthetic and tissue response, absorbable meshes should be reserved for specific clinical indications to temporarily augment primary repair and to limit early suture pull-through and gap formation.

MESH SUTURED REPAIRS

The conceptual underpinnings that the distribution of forces is critical to the creation of a durable laparotomy closure had led to a completely different surgical technique for high tension internal closures [35]. Termed a “mesh sutured repair,” strips of macroporous uncoated polypropylene mesh (Soft Prolene Mesh, Ethicon, Somerville, NJ) 2-cm wide are cut along the blue lines of the mesh. These mesh strips have a suture tied to the end and, using the needle of the suture as an introducing agent, the strips are passed on either side of the abdominal wall and tied like a suture. The large size of the mesh strips resists pull-through, and the heightened total surface area of the device filaments encourages a local deposition of collagenous scar to achieve a durable closure. Humans have been assessed to scar more and regenerate less than other mammalian species [36], and a mesh sutured repair uses this scar response to its advantage. The polypropylene acts as a scar scaffold. It is hypothesized that the mesh suture creates a magnified foreign body response because of its 34 times increased surface area in comparison with standard suture [37]. Although standard monofilament sutures either loosen or dissolve over time, the incorporation process allows for mesh placed through tissues to remain solidly present for lasting support (see Fig. 3).

The efficacy of the mesh strips is most dramatically demonstrated in the 48 contaminated repairs CDC grades 2 to 4 with average hernia widths of 10.5 cm preoperatively by computed tomography scan [38]. Mesh sutured repairs obviate the need to open tissue planes to place a large planar mesh. The skin stays attached to the abdominal wall, preserving its vascularity and wound healing potential. The low infection rates that are documented are thought to be due to rapid incorporation by the tissues and the ability of the human body to deal with small filaments as opposed to larger filaments that are the size of standard laparotomy sutures. If an infection of the mesh strip were to occur, it is immediately under the incision allowing for an office removal. With almost 1 year follow-up, 3 midline hernias recurred for a 6% recurrence rate. These recurrences can then be addressed electively as a CDC class 1 clean hernia. These repairs also are relatively quick to perform, and most recently we have begun to run these mesh strips for the closure. This technique has become widely used at our home institution and has gained traction on a national and global scale.

MESH SUTURE

The logical continuation of the distribution of forces that is somewhere between a suture and a mesh is a mesh suture [39]. The mesh suture is made of multiple small filaments braided and bonded to each other to create the

strength of a larger monofilament suture. Mesh suture represents a significant increase in suture diameter than what is currently available. It is 3 to 10 times larger in diameter than standard sutures for improved distribution of forces and limiting of tissue tearing. These diameters are only possible because the open braid allows the knots to collapse down into a size more keeping with a standard suture. The surface area of the 0 mesh suture is almost 8 times that of the surface area of standard 0 monofilament suture, providing a scaffold for fibrovascular ingrowth and scar formation [16]. Mesh sutures are mostly air, and so the filaments collapse at the knot to become a far lower profile than a similarly sized solid suture. There may be an improved biologic tissue response of small diameter filaments as compared with the use of larger filaments for laparotomy closure [40]. Similar strategies that attempt to augment the natural tendency of humans to form scar and enhance biologic healing include the application of nanofibers made from polyesters [41] and microparticles of silver [42].

An improved suture that limits suture pull-through could help to limit or prevent gap formation. In orthopedics, gap formation refers to minor and incomplete separation of a repair due to tension. In hand surgery, a gap formation of 2 mm is associated with tendon ruptures and scarring. Similarly, 12 mm of gaping of a laparotomy closure over the first 30 days after repair is associated with a 94% chance of incisional hernia formation [43].

By 4 months [44], the physical construct strength of a closure will reach a relatively steady state characterized by scar formation and collagen remodeling. The long-term strength of a laparotomy closure using absorbable sutures is approximately 70% of the unscarred linea alba [45]. Unlike normal unscarred tissues that follow Davis's law that tissues enlarge or hypertrophy with exercise and added use [46], scar does not have pulsatile blood flow, and it deforms and weakens rather than gaining strength. The presence of a permanent, well-incorporated mesh suture may be additive to the 70% scar strength found with absorbable sutures to achieve a lasting closure of the midline abdominal wall.

A recently published preclinical study was performed at an independent laboratory at the Uniformed Services University–Walter Reed National Military Medical Center Department of Surgery that supports many of these concepts [47]. Porcine abdominal walls were closed with various sutures and surgical techniques. The study validated the small bites closures performed predominantly in Europe as having improved breaking strength over large bite closures, but this improvement in breaking strength was only 10% over baseline. Comparison of the number 1 polydioxanone with 1-cm bites and the number 1 mesh suture with 1 cm bites demonstrates a statistically significant 46% improvement in tensile strength for the latter, and this is even before any tissue incorporation takes place.

SUMMARY

Fascial closure and long-term hernia formation continues to be a challenging problem across a multitude of surgical specialties. Understanding wound

healing and physical construct principles is crucial in suture choice and obtaining a reliable repair. The most recent advances in laparotomy closure have focused on the distribution of forces to limit early suture pull-through and gap formation. Advances in suture design may lead the way in improved patient outcomes.

Disclosure

Dr G.A. Dumanian is the inventor and has financial interest in Advanced Suture Inc. and Mesh Suture Inc. He could potentially benefit from changes to established methods to close the abdominal wall, including the use of mesh suture. Neither of the authors has any additional financial disclosures.

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