A Review of Available Prosthetics for Ventral Hernia Repair

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Objective: To review mesh products currently available for ventral hernia repair and to evaluate their efficacy in complex repair, including contaminated and reoperative fields.

Background: Although commonly referenced, the concept of the ideal prosthetic has never been fully realized. With the development of newer prosthetics and approaches to the ventral hernia repair, many surgeons do not fully understand the properties of the available prosthetics or the circumstances that warrant the use of a specific mesh.

Methods: A systematic review of published literature from 1951 to June of 2009 was conducted to identify articles relating to ventral hernia repairs and the use of prosthetics in herniorrhaphy.

Results: Important differences exist between the synthetics, composites, and biologic prosthetics used for ventral hernia repair in terms of mechanics, cost, and the ideal situation in which each should be used.

Conclusions: The use of synthetic mesh remains an appropriate solution for most ventral hernia repairs. Laparoscopic ventral hernia repair has created a niche for both expanded polytetrafluoroethylene and composite mesh, as they are suited to intraperitoneal placement. Preliminary studies have demonstrated that the newer biologic prosthetics are reasonable options for hernia repair in contaminated fields and for large abdominal wall defects; however, more studies need to be done before advocating the use of these biologics in other settings.

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V entral hernia repair (VHR) remains one of the most commonly performed surgical procedures. In the United States alone, approximately 150,000 incisional hernias arise from 1.3 million laparotomies performed annually.[1] As elective repair is commonly performed unless patients have prohibitive comorbidities, incisional hernia repair is a common procedure in the general surgeon's repertoire.[2,3] The results of VHR remain suboptimal, however, with reoperation rates of 12.3% at 5 years and 23% at 13 years.[1] Although distinctions are infrequently made in the literature, all hernias are not the same. They often significantly differ in complexity and size. Consequently, the efficacy of various approaches and prosthetics should always be evaluated with a thorough understanding of the specific characteristics of each hernia. Today, numerous prosthetic materials have become available for surgeons to utilize. The purpose of this article is to review both older and newer prosthetics for VHR and to analyze the benefits of each in complicated situations, such as contaminated and reoperative fields.

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METHODS

This review is based on a systematic search of Medline and PubMed databases to identify articles relating to VHR. The searches were restricted to English language citations from the inception of the databases to June 2009. Our search terms included "incisional hernia," "ventral hernia," "herniorrhaphy," "prosthetic mesh," "biologic mesh," and "bioprosthetic." Relevant articles from selected articles' reference lists were also identified and used in this review. All selected articles were published between 1951 and 2009. Case reports, editorials, and pediatric studies (patients <18 years of age) were excluded from this review.

EVOLUTION OF VENTRAL HERNIORRHAPHY

In 1959, Francis Usher and colleagues[4,5] first described the implantation of Marlex mesh, a knitted, polypropylene, monofilament mesh that remains the most commonly used prosthetic for VHR worldwide. Prior to the 1970s, however, most ventral hernias were repaired primarily, which frequently resulted in excessive tension on the suture line and a high rate of recurrent hernia. Several techniques were introduced to help address the high rate of recurrence. The Nuttall repair method transposes the tendinous attachments along the inferior edge of the rectus muscle to the contralateral pubic symphysis to reinforce primary closure of the fascia in a midline defect.[6] The Keel procedure employs bilateral relaxing incisions in the anterior rectus sheath to decrease tension on the midline closure. In the "separation-of-parts" technique, large myofascial flaps are created by incising the external oblique fasciae, thereby facilitating approximation of the rectus abdominis muscles to the midline.[2,7,8] Aside from the "separation-of-parts" technique, which is time intensive and may result in significant patient morbidity, these seemingly innovative methods are associated with unacceptably high recurrence rates, ranging from 20% to 45%.

The need for prosthetic material to replace native tissues for hernia repair was originally noted over a century ago by Billroth. In 1900, Witzel and Goepel used silver-based mesh fashioned from fine silver filigrees for hernia repair.[9] Although silver has bactericidal properties and yields an exceedingly low recurrence rate following repair, it slowly disintegrates and acts as a tissue irritant. Silver mesh also has been shown to lead to fluid accumulation within tissues and sinus tract formation. However, because of its demonstrated success and the lack of other available prostheses, it was regularly used until the 1950s.

Beginning in the 1940s, the use of other metal prostheses surpassed that of silver mesh. In 1948, tantalum, a malleable, noncorrosive metal, was fashioned in to gauze and used for hernia repair. Tantalum is inert and acts as a strong scaffold for fibrous ingrowth. Published recurrence rates following preperitoneal placement of tantalum gauze range from 1% to 2%.[10] In long-term studies, however, it has been shown to fragment and fracture, leading to patient discomfort and eventual recurrence that has been observed several years after the initial repair.

In the early 1950s, stainless steel mesh was introduced as a substitute for other metal-based mesh prostheses. This relatively inert metal offered several advantages over the other metals, including greater flexibility, freedom from fatigue and fracturing, and rapid tissue encapsulation. A study by Validire in 1986 demonstrated a recurrence rate of only 5% to 10% in a series of 150 large abdominal

incisional hernias repaired with stainless steel mesh.[11] This rate is comparable to that currently reported for available synthetic prostheses. However, with the introduction of magnetic resonance imaging to clinical care, stainless steel mesh has fallen out of favor.[12]

In the 1970s, Rives[13] and Stoppa[14] individually described methods of preperitoneal mesh placement that eliminated excess tension, thereby reducing tissue ischemia and resulting in markedly decreased recurrence rates of 0% to 10% following VHR.[15] More recently, a Cochrane review of 3 trials comparing primary suture repair and repair with mesh demonstrated recurrence rates of 54% and 16%, respectively.[16] These data have shaped the current surgical practice of using mesh during VHR as the standard of care. Multiple types of mesh now afford surgeons several options for use during the surgical repair of fascial defects.

THE IDEAL MESH

Cumberland[17] and Scales[18] originally described the characteristics of the ideal prosthetic in the 1950s, and Hamer-Hodges and Scott[19] adapted the description in 1985. The ideal synthetic mesh possesses 8 characteristics: (1) noncarcinogenic, (2) chemically inert, (3) resistant to mechanical strains, (4) capable of being sterilized, (5) inert to body and tissue fluids, (6) capable of limiting foreign body reaction in the host, (7) amenable to fabrication in the necessary form, and (8) unlikely to produce allergy or hypersensitivity reactions.[19] With the introduction of bioprosthetic mesh, additional criteria for the ideal prosthetic have been proposed. Namely, the material must resist infection, provide a barrier to adhesions on the visceral side, and must respond in vivo similarly to autologous tissue.[20]

To date, there is no mesh that appears to meet all the criteria described by Hamer-Hodges and Scott,[19] as indicated in Table 1. However, prosthetic materials have been greatly refined from stiff, metal coils to the current lightweight, pliable prosthetics. A basic understanding of the physical properties of prosthetics is fundamental to appropriate mesh selection for VHR.

MESH MECHANICS

Every prosthetic has distinct mechanical properties that elicit a blend of chemical mediators and cellular elements, resulting in a unique host response.[20] Certain properties of each mesh, including tensile strength, elasticity, porosity, and method of fabrication, may greatly influence the tissue reaction to the prosthetic. Each patient's response to a prosthetic is different; however, by understanding the variables that may influence the tissue response after mesh implantation, short and long-term outcomes may be improved.[21]

The tensile strength of a prosthetic should be at least equivalent to that of the abdominal wall. *Tensile strength* is the maximum strain or force that a material can withstand without deforming. In a study of 20 healthy, young adults who were observed jumping, lifting weights, and performing abdominal crunches, Cobb et al found that the maximum pressure exerted on the abdominal wall during strenuous activity is 27 N/cm^2 (252 mm Hg). At rest, the pressure exerted on the abdominal wall is approximately 16 N/cm^2.[22] Most prostheses can easily withstand such amounts of pressure, but excessive tensile strength in a prosthetic may result in decreased mesh flexibility, loss of abdominal wall compliance, excessive inflammation, and scarring of surrounding tissues, which all lead to increased patient discomfort.[23]

Another property of synthetic prostheses is porosity. Pores serve as a scaffold for the ingrowth of fibrous tissue. Small pores initiate a strong inflammatory response that may contribute to poor tissue ingrowth. Larger pores allow scar tissue formation with preservation of elasticity, or the ability to return to original shape after stress. However, larger pores may not provide an adequate scaffold in which fibrous tissue may grow. The concept of pore size has been studied extensively, and the ideal size appears to be dependent on the type of prosthetic being used.

During fabrication, synthetic mesh may be knitted or woven. Knitted mesh is processed by interlacing 2 distinct filaments or yarns. It is generally more porous and flexible than woven mesh, but it is weaker because of decreased filament density. Knitted mesh varies in its flexibility and stiffness based on its orientation at the time of implantation. In contrast, woven mesh contains filaments lined in parallel while a second set of aligned filaments is passed alternatively over and under the first set in a perpendicular fashion. Woven mesh is generally tightly packed to minimize separation of the filaments, thus it inherently has a smaller pore size. Woven mesh therefore serves as a poor scaffold for the ingrowth of fibrous tissue.[24]

Every prosthetic stimulates a foreign body reaction after implantation. Some reaction is inevitable and necessary to stimulate tissue fibrosis; however, native tissue is susceptible to a lifelong risk of reaction to the prosthetic. Given the unique properties of each mesh and its interactions within the recipient tissue, machining the ideal mesh as described by Cumberland and Scales has proven quite challenging.

METHODS OF REPAIR

Hernia repair may be performed by (1) primary fascial reapproximation without mesh, (2) primary fascial reapproximation reinforced with mesh, and (3) bridging unopposed fascial edges with

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TABLE 1. Characteristics of the Ideal Mesh Compared With Available Meshes*

Characteristics	Stainless Steel	Polypropylene	Polyester	ePTFE	Absorbable	Composite	Biologics
Noncarcinogenic	√	√	√	√	√	√	√
Chemically inert	√	√	√	√	–	√/–	√
Resists mechanical strain	√	√	√	√	–	√	√
Capable of being sterilized	√	√	√	√	√	√	√
Controlled foreign body reaction†	√	√/–	√/–	√	√	–	√
Amenable to fabrication in the necessary form	√	√	√	√	√	√	√
No allergic or hypersensitivity reaction	√/–	√	√	√	√	√	√
Resistant to infection	√	–	–	–	√	–	√
Barrier to adhesions on visceral side	–	–	–	√	√/–	√	√
Responds similarly to autologous tissue	–	–	–	–	–	√	√

*This table demonstrates how currently used mesh prostheses comply with the characteristics of ideal mesh as first described by Cumberland and Scales.
†All mesh products excite a disorganized foreign body reaction; however, these reactions do not generally interfere with clinical applicability.

mesh. An adjunct used to facilitate a primary repair is the use of component separation, which eliminates the need for a prosthetic. Detailed descriptions of the various techniques for release of the myofascial planes of the abdominal wall are beyond the scope of this article. An important consideration in mesh hernia repair is the specific location of the mesh in relation to the fascial layer. Mesh may be used as an "overlay", in which it is placed anteriorly to the fascia to reinforce primary fascial reapproximation. It may also be used as an "underlay," either preperitoneally or intraperitoneally, lying deep to reapproximated fascial edges. Finally, when placed to span or "bridge" a fascial defect, mesh may also be placed preperitoneally or intraperitoneally.[15] Specific characteristics of the hernia defect and the resultant environment in to which a mesh is placed often dictate the choice of prosthetic (see Fig. 1).

Another determinant of mesh choice is whether repair will be performed laparoscopically or with traditional open techniques. Laparoscopic VHR was first described in 1993 by LeBlanc and Booth[25] and has become a widely used technique in recent years. In this technique, trocars are placed lateral to the hernia defect; after reduction of the hernia contents, a mesh is placed intraperitoneally to bridge the fascial defect. The mesh generally extends 3 to 5 cm beyond the hernia defect and is affixed with spiral tacks or staples.[26]

The advantages of laparoscopic VHR are well-studied and include shorter length of stay and decreased wound infection rates. These benefits are a direct result of the multiple small incisions used for the laparoscopic approach. Because of the physical constraints created by these small incisions and the proximity to intra-abdominal viscera, there are a limited number of products available for repair. Overall, hernia recurrence rates at 5 years were nearly identical between laparoscopic repair and open mesh repair, 29% and 28%, respectively.[27]

TYPES OF MESH

Prosthetics used for VHR are broadly classified in to 3 categories: synthetic polymers, composites, and biologic prosthetics. Synthetics are subdivided in to permanent (nonabsorbable) or absorbable mesh. Among the permanent synthetics are polypropylenes, polyesters, and expanded polytetrafluoroethylene (ePTFE). Polypropylene-based materials are the most commonly used synthetics for hernia repair in the United States[28] and may be further classified as lightweight or heavyweight. Absorbable synthetic prostheses, including glycolic acid (Vicryl), polyglycolic acid (Dexon), and carboxycellulose, are generally reserved for temporary abdominal closure or used in conjunction with permanent synthetics. Composite prosthetics are those composed of more than 1 type of material and are designed for intraperitoneal placement because they minimize adhesion formation. The biologic meshes are acellular collagen backbones derived from allogeneic or xenographic sources that are incorporated in to surrounding tissues. The broad mesh classifications are listed in Table 2.
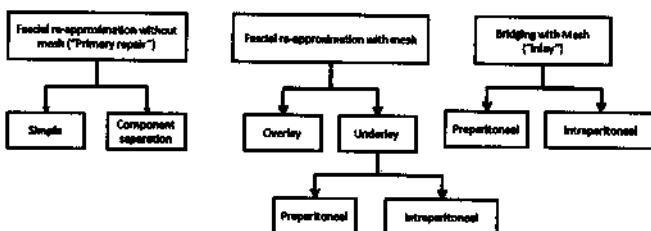

FIGURE 1. Methods of ventral hernia repair.

TABLE 2. Classes of Ventral Hernia Mesh

Prosthetic Class	Types
1. Synthetics	Polypropylene
	Polyester
	ePTFE
	Absorbables
2. Composites	Coatings
	Dual-sided
3. Biologic sources	Human
	Porcine
	Bovine

Polypropylene

Polypropylene is the most commonly used mesh for hernia repair, with more than 1 million prosthetics implanted each year.[28] It is a hydrophobic polymer produced by the polymerization of propylene, a derivative of propane gas.[20] Its rough surface prevents any migration within host tissue. It is extremely resistant to biologic degradation as it is not significantly weakened by tissue enzymes.[9] It can be either woven or knitted and is formulated as a monofilament or in a dual or multifilament arrangement. Polypropylene is typically knitted because this arrangement allows for increased porosity, flexibility, and identical mechanical properties in all directions.[24] Since Marlex mesh was first introduced by Usher in the 1950s, numerous clinical and experimental studies have proven its efficacy for VHR.

The most extensively studied polypropylene prosthetics are the heavyweight meshes, such as monofilamented Marlex and bifilamented Prolene. To calculate forces on the abdominal wall, Klinge et al[29] created a theoretical mathematical model estimating the average pressure on a resting abdominal wall as 16 N/cm^2. Klinge's group calculated the tensile strengths of the most common heavyweight polypropylenes, Marlex and Prolene in both the vertical and horizontal directions. The tensile strengths of these heavyweight prosthetics were 6 times the strength of the normal abdominal wall and far exceeded the maximum abdominal wall tensile strength of 27 N/cm^2 as studied by Cobb et al. Such studies suggest that heavyweight meshes may be overengineered for the mechanical requirements necessary for repairing human abdominal wall defects.

In recent years, however, lightweight polypropylene meshes have emerged that differ significantly from heavyweight mesh in regard to pore size, thickness, tensile strength, and host response (Table 3).[30] Klinge et al also compared the elasticity of the abdominal wall in human cadavers to that of the heavyweight and lightweight polypropylene meshes. Universally, the human abdominal wall had significantly greater elasticity than polypropylene, although the lightweight mesh mimicked human tissues more closely than the heavyweight polypropylene. In addition, patients in whom hernias were repaired with heavyweight Prolene reported chronic pain and a "stiff abdomen" more frequently than those patients whose hernias were repaired with Vypro, a lightweight polypropylene mesh.[31]

In animal studies, heavyweight and lightweight polypropylene prosthetics were noted to shrink significantly after implantation, putting the hernia repair at risk for recurrence at the mesh-fascia interface. In a canine study, a 30% to 50% reduction of polypropylene surface area was observed during a 6-month study period, with lightweight polypropylene shrinking more than its heavyweight counterpart.[32] In a similar porcine model, the percent of contraction did not differ significantly between heavyweight, midweight, and lightweight meshes. The contraction rates were 28% for the heavyweight mesh, 33% for the midweight, and 29% for the

TABLE 3. Types of Synthetic Mesh

Class	Name	Manufacturer	Pore Size	Tensile Strength	Thickness
Heavyweight polypropylene					
	Prolene	Ethicon, Inc.	1–2 mm	89 N/cm	0.6 mm
	Marlex	Bard Inc.	0.1–0.8 mm	59 N/cm	0.65 mm
Lightweight polypropylene					
	Vypro	Ethicon, Inc.	3–5 mm	16 N/cm	0.4 mm
	ProLite	Atrium Medical Corp.	1 mm	56 N/cm	0.5 mm
Polyester					
	Dacron	Dupont	0.3–0.7 mm	ND	0.20 mm
	Mersilene	Ethicon, Inc.	0.6–1.0 mm	19.5 N/cm	0.25 mm
ePTFE					
	Goretex	W. L. Gore and Associates, Inc.	<25 μm	> 16 N/cm	1.0 mm
	Mycromesh	W. L. Gore and Associates, Inc.	Macro- and microporous	> 16 N/cm	1.0 mm
	MotifMESH	Proxy Biomedical	<1 μm	29–33.5 N/cm	0.15 mm

lightweight. Based on these data, a 3- to 5-cm overlap of polypropylene mesh onto healthy, native tissues is recommended during hernia repair.

Heavyweight polypropylene elicits an inflammatory response characterized by dense and rapid encapsulation by host tissue. Although it remains relatively inert in comparison with the meshes that precede it, Costello et al[33] observed physiochemical changes, such as cracking, shrinkage, and reduced compliance in explanted polypropylene. Histologic evaluation of removed heavyweight polypropylene prosthetics demonstrate typical chronic inflammatory changes characterized by foreign body granulomas.[33] In addition, there is a persistent acute inflammatory process characterized by neutrophils and focal fibrinoid necrosis, particularly at the interface between the host tissue and the prosthetic. Conversely, the body's reaction to lightweight mesh is less pronounced, rarely showing signs of acute inflammation.[34] A porcine model demonstrated more scar tissue and capsule formation in heavyweight mesh, with fewer inflammatory cells and a higher degree of incorporation among the lightweight prosthetics.[35] Because the observed inflammatory response to polypropylene is attenuated in prosthetics with less polypropylene content, lightweight mesh theoretically reduces the foreign body response.

In addition to polypropylene content, studies suggest that pore size plays an important role in the degree of inflammation and scar tissue formation around implanted prosthetics. Klinge et al used rats to study heavyweight and lightweight polypropylene mesh with similar polymer surface but differing pore size (0.46 vs 2.8 mm).[36] Results demonstrated that the mesh with smaller pore size and higher polypropylene content had a more intense inflammatory reaction with strong bridging scar formation.[36] In contrast, the more porous lightweight mesh formed a thinner scar framework and the adjacent tissues achieved levels of apoptosis and proliferation that were similar to the physiologic control group. A separate study comparing heavyweight polypropylene (pore size, 1.64 × 0.96 mm) and lightweight polypropylene (pore size, 3 × 4 mm) investigated collagen deposition and tensile strength at explantation. One month after implantation, the lightweight mesh showed tensile strength that was similar to heavyweight Prolene.[37] These findings were attributed to increased deposition of total and mature type I collagen in the more porous lightweight mesh. The results of these studies suggest that greater distance between pores in lightweight mesh allows for improved abdominal wall compliance.[35] Table 3 summarizes the variation in pore size and tensile strength between heavyweight and lightweight polypropylenes.

Despite the widespread use of polypropylene meshes, complications of its use have been observed, including mesh migration, wound infection, hernia recurrence, and functional impairment. Welty et al[38] evaluated outcomes of patients undergoing VHR with Marlex, Atrium heavyweight polypropylene mesh, and lightweight Vypro. Although none of the prosthetics were removed because of infection, the heavyweight monofilaments (Marlex and Atrium) did have slightly higher rates of clinical wound infections, hematomas, and seromas than were associated with Vypro. In all instances, recurrences were always located at the mesh margins, with rates of between 3.4% and 9.6%.[39] Gastrointestinal fistulization was only noted in the heavyweight group. Subsequent research has shown that overall wound infection rates are similar among different polypropylene meshes, estimated to be approximately 3% in uncomplicated hernia repair.[28]

In this study, patients in the heavyweight mesh group had increased reports of paresthesias with both daily and strenuous activities.[39] To evaluate these reports objectively, 3-dimensional stereography was used to calculate abdominal wall mobility. These assessments demonstrated increased abdominal wall stiffness with all polypropylene meshes. The mesh height, in addition to mesh curvature, corresponded with reported symptom severity.[39] In an evaluation of patients who underwent mesh removal, heavyweight Prolene was explanted 40% of the time due to chronic pain, whereas only 6% of Vypro implants had to be removed due to discomfort.

Several studies have demonstrated the propensity of polypropylene to adhere to the bowel wall when placed in direct contact with abdominal viscera. Consequently, polypropylene is now seldom used alone when placing mesh within the peritoneal cavity[32] and is also not suitable for laparoscopic VHR. Despite their disadvantages, polypropylene meshes still remain the most commonly used prosthetics due to their strength, ease of handling, and versatility.

Polyester

Polyester is a multifilament, nonabsorbable, carbon-based polymer that is made from ethylene glycol and terephthalic acid. Unlike polypropylene, it is not susceptible to oxidative stress and is generally hydrophilic. Wolstenholme[40] first used commercial Dacron polyester in 1956 for the repair of inguinal and abdominal hernias. In the 1960s, Mersilene mesh became available; it is a pliable, macroporous mesh consisting of Dacron polyester fibers knitted in to an interlocking pattern.[20]

Current literature offers conflicting reports regarding the safety and efficacy of polyester in the repair of abdominal wall hernias. In a 1991 study, Wantz et al[41] successfully repaired 30 large

incisional hernias with Mersilene mesh due to its ability to conform to the abdominal wall curvature and a robust fibroblastic response that ensured encapsulation. In addition, short-term animal studies of implanted polyester prosthetics have demonstrated several advantages with regard to its biomechanical profile. Research in swine models comparing polyester and polypropylene prosthetics of the same size at implantation demonstrated significantly less contraction after 3 months with polyester mesh.[42] These swine studies also revealed higher rates of incorporation and lower visceral adhesion rates with polyester than with polypropylene.[43]

However, some studies have questioned the efficacy of polyester mesh and its potential for undesired complications. While investigating the incidence of recurrence and other complications between various prosthetics, Leber et al[44] reported that Mersilene mesh repairs have higher infection and recurrence rates and a higher incidence of enteric fistualization than is seen with heavyweight polypropylene mesh. Of note, the prosthetics used in this study were often placed intraperitoneally instead of the traditional preperitoneal location. Therefore, unprotected polyester prosthetics are not recommended for placement in direct contact with the peritoneum unless coupled with a layer to prevent adhesion formation.[45] Like polypropylene, polyester has been shown to be most efficient when used in open repairs with a preperitoneal placement.

Expanded Polytetrafluoroethylene

Another synthetic, nonabsorbable prosthetic, ePTFE, differs from polyester and polypropylene and is shown to have favorable results when placed intraperitoneally. An inert fluorocarbon polymer that is not susceptible to biologic processes, the GORE-TEX Soft Tissue Patch is now the most commonly used ePTFE product (Table 3). Developed in 1963 and first used to repair abdominal wall defects in 1983, ePFTE has demonstrated excellent results with intraperitoneal placement. The side of mesh exposed to the viscera is smooth with pores measuring less than 3 μm, whereas the other side has a larger pore size with small ridges and depressions. This engineering enables collagen ingrowth from the fascia while the visceral side resists cellular penetration and adhesion formation.[20]

A 1994 European animal study comparing ePTFE with polypropylene for VHR demonstrated fewer adhesions in the ePTFE group.[33] However, recurrence of hernias at the interface of the mesh and fascia were more common among the ePTFE prosthetics. As demonstrated in a study by Klinge et al examining foreign body reactions, explanted ePTFE had minimal inflammatory reaction compared with polypropylene and polyester. Furthermore, use of ePFTE pro-duced no fibrous connective tissue interlinking the mesh or forming a fibrous scar capsule, likely contributing to higher recurrence rates with ePTFE mesh.[33]

A rabbit model also demonstrated microporous ePTFE implants to have adhesion rates that were significantly lower than those associated with macroporous polypropylene when placed intraperitoneally and evaluated after 16 weeks.[38] A recent study evaluated outcomes in patients with Prolene mesh placed in the preperitoneal space and ePTFE placed intraperitoneally. There was no significant difference in complication rates between the 2 groups but the polypropylene group did report higher rates of abdominal discomfort.[46] Similarly, studies of laparoscopic VHR with ePTFE demonstrated minimal adhesion rates and enterocutaneous fistula formation, which are 2 dreaded complications of intraperitoneal mesh placement.[47,48] Although ePTFE has proven a reasonable option for intraperitoneal mesh placement and has shown positive results when used for laparoscopic VHR, it is suboptimal for preperitoneal placement as it lacks the tensile strength of the other synthetic meshes and its small pore size is not amenable to the ingrowth of fibrous tissues.

Coated/Composite Mesh

The synthetic polypropylenes and polyesters may be supplemented with coatings to form composite meshes (Table 4). Because of the risk for complications associated with polypropylene and polyester when placed in direct contact with the intra-abdominal viscera, use of a product with temporary degradable-coated strands can provide a barrier between the intraperitoneal contents and the synthetic mesh. Sepramesh is a polypropylene supplemented with Seprafilm, a hyaluronate carboxymethylcellulose layer designed to prevent visceral adhesions. C-Qur and Proceed are 2 monofilament polypropylenes augmented with absorbable omega-3 fatty acids and oxidized cellulose, respectively. Parietex is a polyester-based mesh coated with an antiadhesive collagen layer.

Outcomes based on the use of various coated meshes for intraperitoneal placement have been studied in several animal trials. Jacob et al implanted Parietex, Proceed, and polypropylene (control) intraperitoneally in porcine models and evaluated shrinkage, adhesions, abdominal wall adherence, and tissue ingrowth at 28 days. Parietex had fewer adhesions and histologically promoted a visceral neoperitoneum.[49,50] Bellon et al[51] demonstrated even more profound efficacy of Parietex in rabbit models. Differences in adhesion formation between Parietex and Sepramesh were noted as early as 2 weeks after implantation. Attributes of the different coatings used likely

TABLE 4. Types of Composite Prosthetics

Class	Name	Components	Manufacturer	Pore Size	Tensile Strength (N/cm)
Coated mesh	Ultrapro	LW Polypropylene/Poliglecaprone	Ethicon	3–4 mm	68.6
	Sepramesh	Polypropylene/Seprafilm (carboxy-methylcellulose)	Genzyme Biosurgery	Nonporous bioresorbable membrane	ND
	TiMESH	LW Polypropylene/Titanium coating	GP Surgical	>1 mm	>16
	C-Qur	LW Polypropylene/omega-3 fatty acid	Atrium Medical Corp.	ND	ND
	Proceed	LW Polypropylene/polydioxanone-oxidized regenerated cellulose	Ethicon	2.0 mm	66
	Parietex	Polyester/Collagen-polyethylene-glycerol coating	Covidien/ Sofradim	1.0–1.7 mm	42
Dual-sided	Composix	LW or HW Polypropylene/ ePTFE	Bard	Macro- and microporous	
	DualMesh	Double-sided ePTFE with differing surface properties	W. L. Gore	Nonporous	

contributed to these results. The collagen visceral layer of Parietex is hypothesized to be more stable, preventing it from degrading as quickly as the Seprafilm layer used in Sepramesh.[52]

Similarly, a recent animal model evaluated adhesion formation with multiple composite meshes at 7 and 30 days. C-Qur and Parietex had significantly reduced adhesion formation at 7 days, but this trend diminished at 30 days. This finding suggests that the absorbable layers initially allow for reduced intraperitoneal adhesions, but the antiadhesive properties are lost as they degrade. Parietex was the only mesh that did not allow visceral adhesions to develop at any point in time.[53]

Composites with ePFTE are also used for intraperitoneal mesh placement. Composix, a double-sided prosthetic containing ePTFE and polypropylene, is placed so that the polypropylene lies against the fascia while PTFE abuts the viscera. This product is available in both lightweight and heavyweight strengths. DualMesh is an ePTFE synthetic with 2 functionally unique sides: a macroporous and ridged surface for improved tissue attachment to the fascia, and a smooth, nonporous visceral side designed to prevent intraperitoneal adhesions. The use of DualMesh has become a preferred mesh for laparoscopic VHR.

In a porcine study of laparoscopic repairs with the collagen-coated Parietex mesh and the heavyweight Composix prosthetic, both demonstrated appropriate tissue ingrowth while the Parietex mesh displayed fewer adhesions after 28 days. However, there was no appreciable difference in adhesion strength, ingrowth of the 2 prosthetics, or mesh incorporations.[54] Although laparoscopic placement of the mesh may partially explain the low adhesion rates in both groups, further analysis credited the low adhesion rate to a new mesothelial layer on the Parietex.

A prospective randomized trial examined long-term outcomes between the dual-sided ePTFE DualMesh and the coated-polypropylene Sepramesh. Five months after implantation, there were no significant differences among strength of incorporation, mesh shrinkage, or quantity or quality of adhesions.[55] Interestingly, the DualMesh strength of incorporation continued to increase over time instead of reaching the plateau that is characteristic of most mesh, presumably due to the longer time for encapsulation of the nonporous DualMesh. Composite meshes like DualMesh have proven versatile adjuncts to VHR because the polypropylene layer enables more durable hernia repair while the ePTFE layer minimizes visceral adhesions.

Absorbable Mesh

In contrast to the previously mentioned synthetics that are incorporated in to host tissue, absorbable prosthetics are dissolved by hydrolysis over time. The development of absorbable mesh in the mid-1980s was triggered by the complications that developed when nonabsorbable synthetics were placed in contaminated fields. Dexon and Vicryl, both of which have polyglycolic acid as their main constituent, have become the more commonly used absorbable meshes. Polyglycolic acid is a repeating carbon ester backbone with sidechains of a carbon attached to 2 hydrogen molecules; its chemical properties offer good tensile strength while allowing for gradual dissolution.

Dexon mesh is a knitted homopolymer of polyglycolic acid. Although Dexon has been reported to cause adhesions, 1 long-term study suggests that the adhesions soften with time as the mesh is absorbed.[20] Vicryl, or Polyglactin 910, is a copolymer composed of polyglycolic acid and lactic acid and is available as either a knitted or tightly woven mesh. Both of these absorbable synthetic materials appear to be completely absorbed between 90 and 180 days after implantation.[20]

Absorbable prosthetics are flexible, easy to manipulate, and may be used for closing contaminated abdominal wall defects. They have been successfully used as temporary barriers in contaminated fields to allow for skin closure and wound healing. Because they are absorbable, they do not need to be removed at the time of reoperation. Upon healing, though, a hernia generally occurs where the mesh has been absorbed. Consequently, absorbable prosthetics are rarely used alone for hernia repair in the clean field.

Wound infections can also be managed without removing an absorbable mesh.[56] A 2007 retrospective study in the Netherlands looked at the safety of nonabsorbable and absorbable mesh in the presence of postoperative abdominal wound infection and dehiscence. Regardless of the mesh used, VHR following wound dehiscence or infection had high complication rates. Furthermore, the authors found absorbable polyglactin mesh to have similar rates of complications when compared to their nonabsorbable counterparts. Interestingly, use of the polyglactin was associated with a significantly increased rate of progressive abdominal sepsis.[57] These concerning results have led to the exploration of other alternatives such as negative pressure dressings and biologic prosthetics.

Biologic Mesh

Biologic prostheses are the newest materials available for VHR. At present, these prostheses are derived from the collagen-rich tissues of human, porcine, or bovine sources. The tissues are decellularized with sodium deoxycholate or a similar solvent, which yields a matrix of collagen, elastin, and laminin that serves as supporting strattice for cellular repopulation and neovascularization. These acellular scaffolds may also be cross-linked, which inhibits collagen degradation by blocking collagenase-binding sites, thereby allowing the mesh to maintain its structure for a longer period with slower incorporation in to the adjacent tissue.[18,58]

Several bioprosthetic materials are currently manufactured. Although the basic composition of each is the same (ie, a collagen matrix), the prostheses vary in tensile strength, rate of incorporation, and resistance to infection. The more commonly used biologic meshes are human acellular dermal matrix (HADM), porcine small intestine submucosa (Surgisis), and porcine dermis (Permacol). Table 5 outlines the currently available biologic prosthetics.

Human acellular dermal matrix was first introduced in 1992 for the treatment of full-thickness burn wounds and has been utilized for intraoral resurfacing, facial augmentation, breast reconstruction, and bladder sling reconstruction.[59] Neovascularization starts as early as 3 days after implantation. In 2003, Guy et al first described its use for a novel method of one-stage closure following decompressive celiotomy for abdominal compartment syndrome.[51] Human acellular dermal matrix is most efficacious when used to reinforce a primary repair because its tensile strength remains similar to that of native tissues until incorporation is complete. It can be used in contaminated or irradiated wounds and generally inhibits adhesion formation.

Several series have described eventration or stretching of HADM over time, leading to eventration or possible separation of the prosthetic from fascial edges before complete incorporation. The clinical significance of eventration remains unclear, as it does not appear to correlate to the hernia recurrence rate. Jin et al described universal stretching of the HADM grafts but still showed an estimated 20% recurrence in patients who underwent primary fascial repair with HADM used as reinforcement.[60] Eventration is a unique problem to this particular bioprosthetic, as comparative studies with other bioprosthetics do not demonstrate stretching.[58,61]

Porcine small intestine submucosa is processed to remove cells from the tunica submucosa. It is available as an 8-ply product (Surgisis) in both perforated and nonperforated forms. The perforated mesh facilitates revascularization and cellular infiltration, with full incorporation occurring within 3 to 6 months of implantation. LyoSIS, a lyophilized small intestine submucosa biologic mesh, has

TABLE 5. Types of Biologic Mesh

Type of Mesh	Manufacturer	Source	Material	Capillary Ingrowth	Tensile Strength (N)	Cost ($ per cm²)
Alloderm	LifeCell	Human	Acellular dermis	28 days	144	26.08
AlloMax	Bard	Human	Acellular dermis	ND*	ND	28.00
Flex HD	Ethicon/Musculoskeletal Tissue Foundation	Human	Acellular dermis	ND	ND	ND
Permacol	Tissue Science Laboratories	Porcine	Acellular dermis	7 days	42.7	8.33
Collamend	Bard	Porcine	Acellular dermis	ND	186	16.00
Strattice	LifeCell	Porcine	Acellular dermis	ND	59.9	ND
XenMatrix	Brennan Medical	Porcine	Acellular dermis	ND	ND	ND
Surgisis	Cook	Porcine	Small intestine submucosa	7 days	130 +/-29	3.40
SIS Gold	Cook	Porcine	Small intestine submucosa	7 days	433.6 +/-79.5	ND
Lyosis	Cook	Porcine	Lyophilized small intestine submucosa	ND	ND	ND
FortaGen	Organogenesis	Porcine	Small intestine submucosa	ND	ND	ND
SurgiMend	TEI bioscience	Bovine	Fetal dermis	21 days	ND	22.00
Periguard	Synovis	Bovine	Pericardium	ND	ND	1.90
Veritas	Synovis	Bovine	Pericardium	28 days	26.1	8.60
Tutomesh	Tutogen	Bovine	Pericardium	ND	42	ND

*ND: no published data available.

demonstrated improved incorporation over time when compared with traditional Surgisis because its greater porosity stimulates tissue ingrowth and subsequent neovascularization.[62] Chemically cross-linked acellular porcine dermis (Permacol) inhibits degradation of the collagen matrix. This bioprosthetic produces less surrounding inflammation and fibrosis than Surgisis but also demonstrates only limited vascular ingrowth. Although several different biologic mesh products are currently available for VHR, including bovine pericardium and dermis, long-term studies evaluating their efficacy are not yet available. To date, there is no evidence that porcine and bovine sources elicit an antibody response that may result in rejection.[63,64]

Current data suggest that the tensile strength of different biologic prostheses varies significantly. Cross-linked porcine dermal matrix exhibits tensile strength at 90 days after implantation that is indistinguishable from polypropylene synthetic mesh.[65] Ayubi et al[57] created a rat model to compare tensile strength, collagen deposition, and neovascularization in Permacol and Surgisis. The study demonstrated increased tensile strength in Surgisis over Permacol without a significant increase in adhesion formation.[57] Similarly, Peri-Guard, a cross-linked prosthetic derived from bovine pericardium, demonstrates significantly increased tensile strength when compared with its non–cross-linked bovine pericardium counterpart, Veritas.[58]

Biologic mesh may be used for both intraperitoneal and extraperitoneal placement. A retrospective review of 39 abdominal wall reconstructions using HADM as an overlay following primary fascial closure demonstrated a low complication rate and low recurrence. The overall recurrence rate in patients with uncomplicated biologic mesh repair was reported as 5% during a 15-month follow-up.[66]

Various biologic mesh products have also been studied in the intraperitoneal "underlay" position.[61,67] Rauth et al compared porcine VHR with SiS Gold, LyoSiS, and ePTFE, with all meshes placed intraperitoneally. Each of the specimens in this study incorporated well in to surrounding tissues, but only the bioprostheses resulted in neovascularization and tissue remodeling.[59] Ex vivo studies demonstrate that the intraperitoneal location results in a durable repair. Despite decreased tensile strength of the bioprosthetic mesh at 10 to 14 days post implantation, the tensile strength actually exceeds that of the surrounding tissues as remodeling continues.[68] At this time, there is

only limited data available regarding the use of biologic prosthetics intraperitoneally for laparoscopic VHR, though results of repair with Surgisis are promising.[69]

As a fascial bridge, however, biologic mesh does not fare well, as it often stretches with time, which is also referred to as eventration or even recurrent hernia. A study by Blatnik et al followed 11 patients who underwent bridging hernia repair with HADM. Traditionally, an abdominal defect that cannot be reapproximated is bridged with either a permanent mesh or absorbable mesh (such as Vicryl) to avoid evisceration, understanding that hernia recurrence is almost inevitable.[70] Patients may return for elective hernia repair several months later. To avoid this 2-staged procedure, HADM was used to bridge fascial defects in 11 patients, all of whom had complex abdominal wounds, including infected prosthetic mesh, nonhealing wounds, and enterocutaneous fistulae. In 2 years of follow-up, 80% of the patients evaluated in this study developed hernia recurrence, confirming that bridging abdominal wall defects with HADM does not provide a viable long-term solution to a difficult surgical problem.[70] Several other groups demonstrated poor results with bridging repair, including Candage et al,[67] who showed 60% recurrence in those undergoing bridging repair with HADM. Patton et al followed 67 patients after HADM repair in potentially contaminated or infected fields. Mesh position was the sole statistically significant factor for recurrence, with bridging "interposition" placement leading to the majority of recurrences.[71]

The most promising advantage of biologic mesh is the ability to use it in contaminated or infected surgical wounds. Because biologic mesh is revascularized and incorporated in to host tissue, it elicits a markedly diminished foreign body response as compared with its synthetic counterparts. The relatively low concentration of inflammatory cells surrounding biologic mesh is thought to contribute to its successful use in contaminated fields. Several studies have demonstrated that biologic mesh may be safely placed in to contaminated fields.[62] In a rabbit model, Milburn et al[72] compared VHR with different prostheses after inoculation of the surgical site with *Staphylococcus aureus*. The group undergoing HADM hernia repair had decreased adhesion and abscess rates compared with the PTFE repair group.[72] In one of the larger series performed to date, Diaz et al[73] studied 75

patients following VHR with HADM in a compromised surgical field, yielding only a 16% recurrence rate. Low recurrence rates have also resulted from high-risk patients undergoing abdominal reconstruction with HADM, such as those with irradiated abdominal walls.[60]

Many of the studies using biologic mesh in compromised surgical fields carry rates of local wound complications that are consistent with the overall wound infection rate of 25% to 50% in a contaminated surgical field.[74] Although the complication rate using biologic mesh in an infected setting is not dramatically different from that of primary fascial repair or synthetic mesh repair, hernia recurrence remain lowest with use of biologic mesh and removal of biologic mesh due to overwhelming infection is a rarity.[70,71,75,76] Diaz et al[72] studied 240 patients following complex VHR with HADM. All but 5% of the patients had complicating factors for VHR, including previous recurrence, concurrent bowel resection, or fistula takedown. In this study, surgical site infections developed in 40% of patients following HADM hernia repair, although the hernia recurrence rate was only 17%. Despite the high rate of surgical site infection, the recurrence rate is congruent with synthetic repair in a clean operative field, and secondary surgical procedures were avoided in these patients.[63] Similarly, Kim et al[77] studied 29 patients following complex HADM hernia repair. Surgical site complications, including infection or hematoma, occurred in 45% of patients, but 89% maintained integrity of hernia repair at 6 months, even in the presence of superficial wound compromise.[74]

Unlike HADM, data regarding placement of Surgisis and Permacol in contaminated fields are conflicting. In a recent study of 55 abdominal wall repairs, many of which were performed under contaminated conditions, Surgisis repairs demonstrated an overall complication rate of 66%, with 39% of patients developing wound dehiscence, and 39% developing hernia recurrence.[78] Similarly, Ueno et al studied 20 patients following VHR with Surgisis in contaminated fields, noting a 50% wound complication rate and 30% hernia recurrence rate.[71] Conversely, Franklin et al studied laparoscopic VHR with Surgisis in contaminated fields, demonstrating retention of tensile strength, low recurrence rates, and low infection rates in patients with intraperitoneal Surgisis.[69] A prospective study of 7 patients undergoing complicated VHR with Permacol supported its use for incisional hernia repair with concomitant bowel resection as only 1 patient in this study developed a postoperative complication (pneumonia) and no recurrences occurred in 11 months of follow-up.[77] Ott et al[79] argue, however, that Permacol elicits a profound inflammatory response when used in contaminated fields and is associated with suppurative infections. As consistent data are not yet available, more extensive studies of the biologic prostheses other than HADM are needed to fully elucidate their response in contaminated fields.

The biologic mesh family has introduced a competitive alternative to traditional staged abdominal closure for complicated abdominal wounds. Successful use may preclude the need for 2 surgeries, and biologic prostheses are not as susceptible to infection as are synthetic prostheses. Despite studies demonstrating tensile strength similar to that of synthetic prostheses or the native tissues following incorporation, biologic mesh has not yet been studied extensively for uncomplicated VHR.

COST

Although a myriad of options are available in VHR—choice of mesh, technique, and position of mesh—the surgeon's approach is generally dictated by the clinical situation. All other factors being equal, however, a cost comparison of various types of repair must be considered, particularly given the current climate of health care.

Mesh hernia repair clearly results in a more durable repair than primary fascial reapproximation. A Swedish study led by Israelsson performed a cost comparison of primary suture repair and polypropylene mesh repair.[80] Despite increased operative and anesthetic time with mesh repair in this study, the mesh repair group had a decreased cumulative hospital stay and fewer missed workdays. The resultant analysis demonstrated an overall savings of approximately 6000 Swedish kronor per patient (US $787.00) for those undergoing mesh repair.[81]

Since its adoption, laparoscopic repair has been viewed as a costly alternative to open surgery because specialized instruments are required, and operative times often exceed those in open repair. Beldi et al[80] analyzed total operative costs of laparoscopic and open hernia repair and concluded that overall costs for laparoscopic hernia repair with composite polypropylene mesh averaged approximately 2000 Euros (US$2800) less than open repair with lightweight polypropylene mesh. The cost savings resulted from decreased postoperative care requirements and length of hospitalization in laparoscopic VHR patients. A study by Bencini et al[82] echoes these findings—a study of 91 patients demonstrated similar overall costs for open and laparoscopic VHR (3936 Euros and 3091 Euros, respectively) as the decreased hospital stay in the laparoscopic group compensated for increased operative times for laparoscopic repair.

There is a wide distribution in the costs of various mesh products. Human-based prostheses are the most expensive with HADM, averaging approximately $26.00/cm^2. Bovine and porcine-based products are costly as well, ranging from $8.60 to $22.00/cm^2. On the other hand, synthetic products are more favorably priced, with absorbable Vicryl mesh costing $0.20/cm^2 and polypropylene mesh costing less than $1.00/cm^2.[23,76,83] Clearly the type of mesh chosen for repair may influence the total cost of VHR in addition to the method of repair and operative time.

FUTURE DEVELOPMENTS

Biologic mesh serves as a collagen scaffold to support cellular proliferation and revascularization in VHR.[84] Current biologics contain fibrillar collagen that afford tensile strength and structural integrity to native tissues, while fibronectin and laminin direct formation and stabilization of blood vessels and provide attachment sites for endothelial cells and fibroblasts.[85] Various growth factors, including vascular endothelial growth factor (VEGF) and fibroblast growth factor (FGF-2) reestablish local vascular supply and rid developing tissues of debris and metabolic waste.[86] As biologic mesh continues to gain widespread acceptance, techniques to increase angiogenesis and incorporation rates are continually being studied. Specifically, endothelial progenitor cells harvested from bone marrow, which can differentiate in to vascular and nonvascular elements, have been proposed as a method to stimulate vascular regeneration.[87,88] Similarly, the topography of the acellular matrices may be modified with plasma clots or fish scales to improve cell adhesion.[89,90] Although these technologies are still being developed and are currently only in experimental phases, the capability to improve VHR strength and integrity is promising.

CONCLUSIONS

Synthetic mesh remains a cost-effective, durable solution for most VHR (Figs. 2 and 3). Lightweight polypropylene mesh has recently proven a comfortable, affordable option for mesh VHR. As laparoscopic VHR has become increasingly popular, a niche has developed for ePTFE and composite mesh, as they are safely used intraperitoneally.

In the past several years, biologic prosthetics have been introduced for VHR. These prostheses are advantageous in that they may be used intraperitoneally or extraperitoneally; however, they are generally expensive and have not proven a cost-effective solution for uncomplicated VHR.[91]
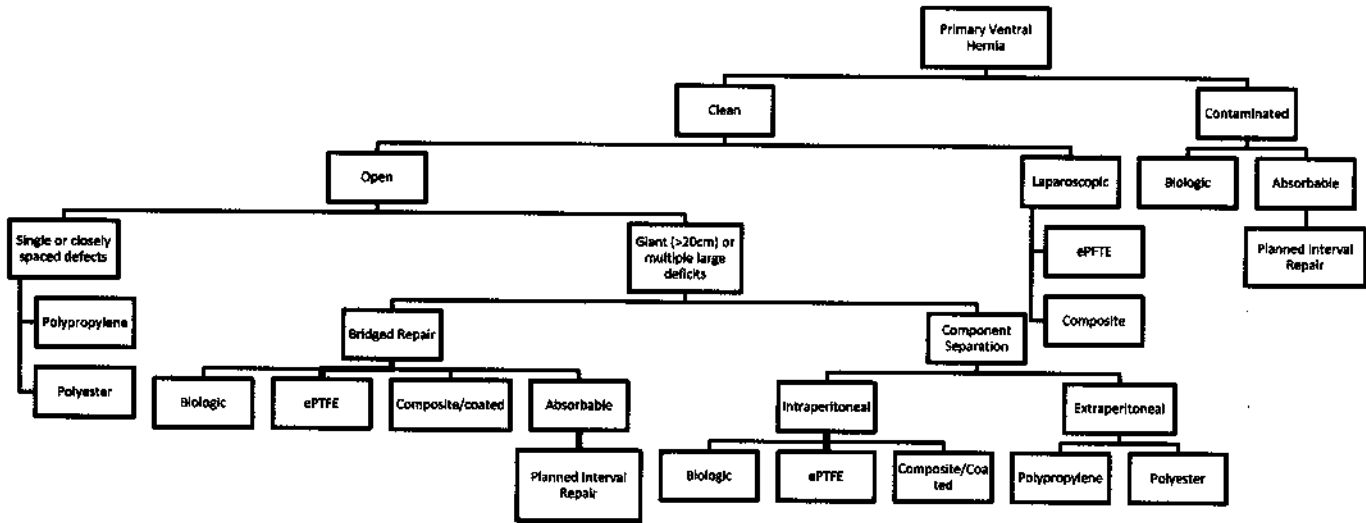
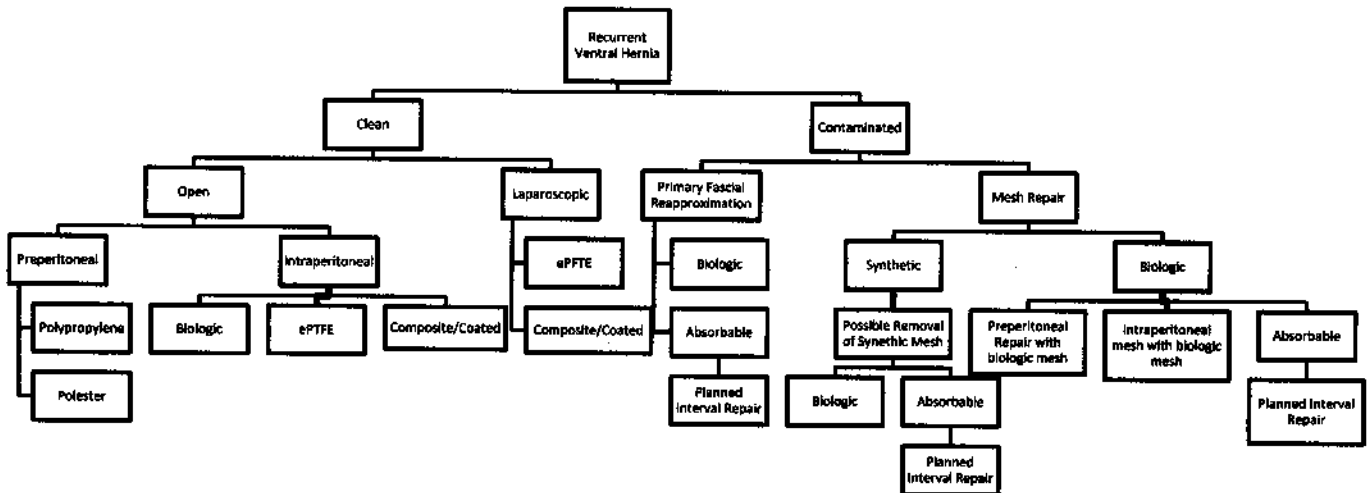**FIGURE 2.** Mesh use guidelines for primary hernia repair.

FIGURE 3. Mesh use guidelines for recurrent hernia repair.

There are 2 specific situations in which the biologic prostheses have demonstrated distinct advantages over synthetic mesh for VHR. In complex ventral hernias (ie, hernia repair in a reoperative field, contaminated field, or performed in conjunction with intra-abdominal surgery), biologic mesh resists infection better than synthetic mesh. Complex hernia repair results in high complication rates, with infectious complications necessitating removal or extensive débridement of synthetic mesh. Biologic mesh, however, reduces the risk of reoperation or extensive postsurgical wound intervention following complex hernia repair.[64]

Biologic mesh may also be used in abdominal wall reconstruction. Previously patients with large abdominal wall defects had undergone a sequential repair; biologic mesh can be used for one-staged repair because it serves as a barrier for intraperitoneal contents and as a definitive solution to prevent future hernia. One-staged repair may save patients the morbidity and cost of a second surgical procedure.

Currently, there are only a few studies comparing the efficacy of different biologic prostheses and the true longevity of biologic VHR is not yet known. If ongoing analyses continue to support biologic prostheses, future gold-standard methods of complex hernia repair may include biologic mesh.

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