

Visceral adhesions to hernia prostheses

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Abstract

Purpose To report our experience with abdominal adhesion formation to various synthetic and biologic prosthetic materials in a rat ventral hernia model.

Methods A total of 14 prostheses, nine synthetic, four biologic, and one bioresorbable, were evaluated in the rat. Two synthetic prostheses had bioresorbable coatings and one consisted of synthetic and bioresorbable materials woven together. The model involved the removal from the midline of a 2.5×2.5 -cm segment of full-thickness ventral abdominal wall with the test prosthetic material sewed into the defect, thus, exposing the viscera directly to one surface of the prosthesis. There were four or more rats in each group. Adhesions were assessed at autopsy 7 days after operation or later. The results were expressed as the percentage area of prosthesis surface involved.

Results All 14 of the tested prosthetic materials induced adhesions. Vicryl Mesh® and the four biologic varieties had lesser overall adhesion coverage than the bare synthetic prostheses. Sepramesh® developed the least adhesion coverage (15%). The two synthetic materials with bioresorbable coatings had smaller areas involved compared to bare synthetic prostheses.

Conclusions All of the tested prostheses attracted adhesions. Biologic prostheses had smaller areas of coverage compared to synthetic prostheses. Barrier surfaces on synthetic meshes were associated with a much lesser extent of adhesion involvement.

Keywords Postoperative adhesions · Prosthesis · Surgical mesh · Ventral hernia

Introduction

The reported incidence of postoperative abdominal incisional hernia generally ranges between 10 and 15% [1–3]. Approximately 100,000 such hernias are repaired each year in the United States [4]. Recurrence rates after anatomic tissue approximation with sutures range from 31 to 54% [5, 6]. The use of prosthetic materials has significantly reduced hernia recurrence rates, usually to under 10% [7].

Adhesions to intraperitoneal prosthetic surfaces occur in 80–90% of patients [8]. Such adhesions can result in bowel obstruction, but the actual incidence directly caused by viscera to prosthesis attachments is not known. Another major consideration is that subsequent operations are made more difficult [9–13]. Operative strategies designed to avoid exposure of the mesh surface to the abdominal viscera include interposition of the intact hernia sac, peritoneal reapproximation, and covering the prosthesis with omentum.

Various approaches to inhibit the formation of adhesions to mesh have been developed. Some involve a bioresorbable layer that is attached or fused on the macroporous mesh surface exposed to the abdominal viscera (Sepramesh®, Proceed®, Parietex®, C-QUR™). A bioresorbable coating on the mesh surface provides mechanical separation of raw or injured peritoneum from the mesh, thereby, reducing adhesion formation. Absorption of the coating occurs by enzymatic degradation and physiological uptake. Residence time varies according to the agent. Manufacturer-reported experiments have shown that the physical integrity of the coating dissipates variably between 2 days

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and 3 months after operation, depending on the coating agents [14]. Materials used include polylactic acid, oxidized cellulose, polyethylene glycol, omega-3 fatty acids, and sodium hyaluronate with carboxymethylcellulose.

An anti-adhesive layer fused on the prosthesis must be non-toxic, well tolerated in the abdomen, and, most importantly, it should discourage visceral attachments to the surface of the prosthesis from the time of the operation until the injured peritoneum and prosthesis surface are covered with a complete layer of mesothelial cells. This occurs 5–7 days following operation and prevents further adhesions [15, 16].

Other variables related to adhesion formation, suggested mostly by the manufacturers, include the structure of the mesh, woven or knitted, pore size, thickness of the mesh, and the diameter of the fibers. These factors do not pertain to the grossly smooth, microporous synthetic surface.

Biologically derived prostheses have been said to induce fewer adhesions, theoretically because of increased “biocompatibility” and lesser foreign body reaction. An important consideration with these materials is the chemical treatments used to effect decellularization and other processes which induce collagen cross-linking. Data associating these chemical processes with the extent of adhesion formation have been inconclusive.

Our laboratory has investigated adhesion formation for a number of years. We have taken a particular interest in the adhesiogenic properties of various hernia prostheses, synthetic and biologic. The purpose of this study was to describe our experience over these years regarding the incidence and extent of abdominal adhesions to a number of commercially available synthetic and biologic hernia prostheses. In many instances, these were control groups for anti-adhesion studies. Because of the retrospective character of the report, the numbers in each group vary and, thus, do not allow rigid statistical comparisons. However, the wide differences among the groups were obvious and do permit the useful conclusion that all prosthetic materials cause adhesions, some much more than others.

Materials and methods

Animals

Mature, female Sprague–Dawley rats weighing between 300 and 425 g were obtained from Charles River Laboratories, Inc. (River Falls, WI). The rats were individually housed in polycarbonate cages with free access to food and water, in a controlled environment with temperatures of ranging from 66 to 76°F and a 12-h light–dark cycle. The animals were cared for by the University of Minnesota Research Animal Resources Department in accordance

with the principles in the Guide for Care and Use of Laboratory Animals, NIH publication, revised in 1996. The animals were acclimated for a minimum of 7 days before initiation of the study. They were fed a commercially available rodent diet (Teklad Rodent Diet) and tap water, ad libitum, throughout the duration of the study. The animals were monitored daily by physical examination. This protocol was approved by the Institutional Animal Care and Use Committee of the University of Minnesota.

Surgical technique

Only healthy-appearing animals with normal appetite were used. Anesthesia was induced with an intraperitoneal injection of sodium pentobarbital, 30–40 mg/kg. The abdomen was shaved and prepared with povidone–iodine solution. A 3-cm midline skin incision was made and subcutaneous flaps undermined far enough to accommodate a 2.5-cm square defect. A 2.5 × 2.5-cm segment of full-thickness ventral abdominal wall was excised from the midline. Three by three-cm prostheses were sewn to the cut edges with a continuous 4–0 polypropylene suture, thus, exposing the viscera directly to the prosthesis. Care was taken to evert the edges of the prostheses toward the subcutaneous tissue. The overlying skin was closed with running intracuticular 5–0 vicryl (polyglactin 910) suture.

Groups (prostheses)

Rough surfaces

Marlex [®]	Heavyweight macroporous polypropylene woven mesh, C. R. Bard, Inc., Murray Hill, NJ; <i>n</i> = 39.
Surgipro [™]	Heavyweight macroporous polypropylene knitted mesh, US Surgical, Norwalk, CT; <i>n</i> = 6.

Smooth surfaces

Composix E/X Mesh [®]	Heavyweight macroporous polypropylene woven mesh with a unilateral expanded polytetrafluoroethylene coating, C. R. Bard, Inc., Murray Hill, NJ; <i>n</i> = 15.
Dual Mesh [®]	Expanded polytetrafluoroethylene with two distinct surfaces: a smooth closed structure surface for reduced adhesion attachment and a rough surface for faster tissue attachment, W. L. Gore & Associates, Inc., Flagstaff, AZ; <i>n</i> = 10.

- MycroMesh®** Expanded polytetrafluoroethylene with a microporous surface, W. L. Gore & Associates, Inc., Flagstaff, AZ; $n = 4$.
- Soft Tissue Patch®** Smooth expanded polytetrafluoroethylene microporous mesh, W. L. Gore & Associates, Inc., Flagstaff, AZ; $n = 5$.

Bioresorbable synthetic materials alone or woven with permanent synthetic materials

- Vicryl Mesh®** Knitted macroporous mesh composed of polyglactin 910 fibers, Ethicon, Somerville, NJ; $n = 13$.
- Vypro Mesh®** Lightweight knitted macroporous mesh composed of braided polyglactin 910 interposed with polypropylene fibers, Ethicon, Somerville, NJ; $n = 5$.

Synthetic materials with a bioresorbable coating

- Parietex®** Macroporous polyester woven mesh with a unilateral collagen/polyethylene/glycol/glycerol fused film coating, US Surgical, Norwalk, CT; $n = 7$.
- Sepramesh®** Lightweight macroporous polypropylene woven mesh with a unilateral sodium hyaluronate–carboxymethylcellulose film coating and with interwoven polyglactin 910, Genzyme Corporation, Cambridge, MA; $n = 20$.

Biologic materials

- AlloDerm®** Acellular human dermal matrix—non cross-linked, LifeCell, Branchburg, NJ; $n = 4$.
- Peri-Guard®** Acellular bovine pericardium—collagen cross-linked by glutaraldehyde, Synovis Surgical Innovations, St. Paul, MN; $n = 16$.
- Permacol®** Acellular porcine dermis—collagen cross-linked by isocyanate, Tissue Science Laboratories, Andover, MA; $n = 10$.
- Veritas®** Acellular bovine pericardium—collagen non cross-linked, Synovis Surgical Innovations, St. Paul, MN; $n = 16$.

Autopsy

The animals were euthanized with intraperitoneal sodium pentobarbital/phenytoin sodium, 0.1 ml (390 mg/50 mg per ml). A U-shaped apron incision was made to fold back the ventral abdominal wall containing the prosthesis.

Adhesion quantitation

The evaluation of adhesions was carried out at autopsy on or after postoperative day 7. We and others have previously observed in the rat that no additional adhesions develop beyond 7 days after operation [14, 15, 17]. The surface of the prosthesis was visually divided into four quadrants to help estimate the percentage of the surface area involved. Specimens were photographed for later review and comparison.

Statistical analysis

Statistical differences were determined using a one-way analysis of variance (ANOVA) and the Tukey–Kramer multiple comparison test. $P < 0.05$ was considered to be significant. All calculations were performed using the GraphPad InStat 3 statistics program (GraphPad Software, Inc., San Diego, CA).

Results

All animals lived throughout the study and no complications were observed, except inconsistent subcutaneous fluid collections. These did not correlate with adhesion coverage or severity.

Table 1 summarizes the findings with respect to the presence of adhesions and the percentage area of the prosthesis surface involved.

Biologic prostheses had less area covered by adhesions than bare synthetic prostheses (29 vs. 86%, $P < 0.001$). Of the coated synthetic prostheses and overall, Sepramesh® had the smallest average adhesion coverage (15%). MycroMesh® had the most extensive adhesion area (100%). Vicryl Mesh® developed a smaller area of adhesions than the synthetic prostheses (44 vs. 86%, $P < 0.001$). The presence of polyglactin 910 braided with polypropylene fibers (Vypro Mesh®) did not significantly reduce adhesion formation compared to plain polypropylene mesh. Sepramesh® and Parietex® had smaller adhesion coverage compared to synthetic prostheses without a coating (19 vs. 86%, $P < 0.001$). Sepramesh® was the prosthesis with the lowest incidence of adhesions, with 9 of 20 prostheses having zero adhesions. None of the synthetic prostheses had zero adhesions. No significant differences in adhesion coverage were observed among the collagen cross-linked and non cross-linked biologic prostheses.

Weight, pore size, fiber diameter, weave and texture of the synthetic bare mesh materials, and the cross-linkage of biologic prostheses did not seem to influence the adhesion extent.

Table 1 Adhesion formation

Prosthesis	Material	Incidence of adhesion involvement	Adhesion coverage, mean % (SEM)
Rough surfaces			
Marlex [®]	Heavyweight macroporous PP woven mesh	39/39	92 (2)
Surgipro TM	Heavyweight macroporous PP knitted mesh	6/6	96 (4)
Smooth surfaces			
Composix E/X Mesh [®]	Heavyweight macroporous PP woven mesh with a unilateral ePTFE coating	15/15	62 (8)
Dual Mesh [®]	ePTFE, closed structure smooth surface for reduced tissue attachment and a macroporous surface for tissue attachment	10/10	92 (7)
MycroMesh [®]	ePTFE with a microporous structure with regularly spaced macropores	5/5	100 (0)
Soft Tissue Patch [®]	Smooth ePTFE microporous mesh	5/5	76 (16)
Bioresorbable materials alone or woven with synthetic materials			
Vicryl Mesh [®]	Knitted macroporous mesh composed of polyglactin 910 fibers	13/13	44 (10)
Vypro Mesh [®]	Lightweight knitted macroporous mesh composed of braided polyglactin 910 and PP fibers	5/5	73 (18)
Synthetic materials with a bioresorbable coating			
Parietex [®]	Macroporous polyester woven mesh with a unilateral collagen/polyethylene/glycol/glycerol fused film coating	4/7	23 (14)
Sepramesh [®]	Lightweight macroporous PP woven mesh with a unilateral sodium hyaluronate–carboxymethylcellulose film coating fused with interwoven polyglactin 910	11/20	15 (5)
Biologic materials			
AlloDerm [®]	Acellular human dermal matrix (non cross-linked)	4/4	26 (6)
Peri-Guard [®]	Acellular bovine pericardium (collagen cross-linked by glutaraldehyde)	15/16	35 (9)
Permacol [®]	Acellular porcine dermis (collagen cross-linked by isocyanate)	9/10	30 (6)
Veritas [®]	Acellular bovine pericardium (collagen not cross-linked)	12/16	22 (8)

PP polypropylene, ePTFE expanded polytetrafluoroethylene

Discussion

Adhesion formation has been one of the most extensively studied areas in surgery, but its pathophysiology still lacks conclusive data. The main trigger is mesothelial cell insult, which may be caused by a variety of stimuli (trauma, ischemia, desiccation, foreign body, etc.). After the initial insult, an inflammatory response begins and predominates during the first 24–48 h. Acute inflammation results in increased capillary permeability and an outpouring of a fibrinogen-rich exudate follows. The extrinsic coagulation pathway plays a major role in this initial phase. The interaction between the soluble coagulation factor VIIa and tissue factor, which is bound to cell membranes, sets a platform for fibrin deposition by converting fibrinogen to fibrin. Platelets have also been implicated in this initial deposition of fibrin and are thought to provide a scaffold for fibrin deposition [18]. Insoluble fibrin from various sources serves as the

initial, provisional matrix that functions as a docking site for signaling molecules and inflammatory cells. This later translates into the formation of a fibrin band between two apposed serosal surfaces. After 5–7 days, proliferating fibroblasts infiltrate the fibrin scaffold, collagen and other connective tissue proteins are deposited, and neovascularization occurs, to produce a fibrous adhesion.

The production of a new mesothelial layer will occur within 5–7 days [15, 19]. This layer is resistant to new adhesions forming. Mesothelial cell generation proceeds in the same manner for adhesion surfaces. They appear from within a denuded area and not from ingrowth from the edges of healthy peritoneum. The repair time of a deperitonealized area is not relative to its size but tends to occur over the same period of time, independent of its size. The process of postoperative adhesion formation begins during surgery and, while the severity may change over weeks and months, the incidence of an adhesion, whether it develops

at all, is determined within the first 5–7 days following peritoneal injury [15].

The experimental evaluation of adhesion formation to hernia prostheses has also been one of the most widely studied topics in the field of surgical research. Various hernia prostheses have been evaluated in multiple animal models. The most frequently employed animal model has been the rat and involves the repair of a full-thickness abdominal wall defect. This model allows for direct exposure of the intra-abdominal viscera to the hernia prosthesis. Others have combined this model with cecal abrasion and the creation of ischemic areas of parietal peritoneum [20]. The addition of extra adhesiogenic stimuli in the abdomen may distract or enhance adhesion formation to the hernia prosthesis being evaluated and lead to biased results.

The assessment of adhesion formation to hernia prostheses has included incidence, extent, and quality. Incidence, the most simple and objective of these criteria, allows identifying those animals that develop any adhesions at all, versus those with none. The extent of the hernia prosthesis involved with adhesions is also fairly objective because of the defined site at the time of implantation. The presence of the hernia prosthesis allows for reliable quantitation of the percentage area involved on a planned two-dimensional flat surface. Most of the published scoring systems for adhesion formation evaluate adhesion quality severity, tenacity of attachments, thickness, breaking strength, or difficulty of separating the involved surfaces by dissection. These criteria are necessarily subjective and have been shown to suffer from interobserver variations [21]. Even if such parameters could be objectively measured, what do they mean? Although the strength of adhesions definitely makes reoperations more difficult, it has not been associated with the likelihood of future intestinal obstruction. Adhesion density has little significance with regards to the sequelae it can produce. We found by sequential laparoscopy that adhesions are present within 24 h and increase for up to 7 days [15, 22]. Thereafter, no new adhesions form, nor do any disappear. Each fibrin attachment matures into a fibrous adhesion containing collagen and blood vessels [23]. From a practical point of view, the early tensile strength of the band has little relevance, if any. It must be rare that a mature adhesion actually breaks.

Choosing a prosthesis for repairing a ventral hernia defect can be a dilemma. Currently, there are more than 30 different products on the market for incisional hernia repair [24]. Factors in choosing include: (1) the characteristics of the hernia—size and location; (2) bacteriologic status of the operative field—sterile, contaminated, or infected; (3) the possibility of avoiding direct exposure of the abdominal viscera to the implanted prosthesis; (4) the method of fixation of the prosthesis; and (5) the operative approach (laparoscopic vs. open).

Subsequent laparotomies in patients with previous synthetic mesh hernia repairs and direct visceral exposure almost always require lysis of adhesions to the mesh. This may prove very difficult when viscera are tightly fused to porous mesh. Enterotomies are fairly common and the resulting contamination limits the choices if new mesh is required. In this regard, there are ample long-term followup data on the traditional synthetic prostheses. Halm et al. reported a complicated perioperative course in 76% of patients (30 of 39) who underwent relaparotomy after previous incisional hernia repair when synthetic mesh had been placed intraperitoneally [25]. Small bowel resections were necessary in 21% of these patients. Enterocutaneous fistulas developed in two. Late results with coated synthetic and biologic prostheses placed intraperitoneally are less mature, but appear to be superior [26–28].

Coated prostheses were introduced in 2000. We report here that these materials definitely ameliorate but do not eliminate adhesions to the mesh surfaces [22]. Parietex® (polyester mesh with a collagen coating) and Sepramesh® (polypropylene mesh with sodium hyaluronate–carboxymethylcellulose coating) have been well tolerated in situations where visceral exposure is unavoidable, as is inherent to the laparoscopic approach.

Very little is known regarding the difficulties of reoperation in patients who have undergone incisional hernia repair with synthetic prostheses that have a bioresorbable coating. There are no data showing what occurs to the barrier agents in the face of contamination. It is doubtful that the coating can alter the occurrence of infection, and such materials are best avoided in this situation. In the experimental setting, Schreinemacher et al. found that Parietex® and C-QUR™ (polypropylene mesh coated with a layer of omega-3 fatty acids) had significantly less adhesions at day 7 compared to Marlex®, TiMesh®, and UltraPro® (polypropylene composites with titanium and polyglycaprone, respectively), and Proceed™ (polypropylene mesh coated with a layer of cellulose) [29]. Regardless of the type of mesh, the fixing sutures and cut edges of the mesh were preferential sites for adhesion formation. By day 30, phagocytosis of the coating was seen for all meshes with layered coatings. The authors found poor incorporation of all prostheses into the rat abdominal wall. Although interesting, this finding may be related to the experimental model that the authors employed, which did not involve the repair of an abdominal wall defect. The prostheses evaluated in this study were simply fixated to the ventral abdominal wall through a laparotomy incision.

Arnaud et al. used ultrasound examination to assess visceral adhesion formation to intraperitoneally placed prostheses in patients who had undergone open ventral incisional hernia repair with either Parietex® ($n = 51$) or Mersilene® (macroporous polyester fiber woven mesh,

$n = 22$) [30]. Seventy-seven percent of the patients showed visceral adhesions to the prosthesis in the Mersilene® group and 18% in the Parietex® group. These findings are similar to our observations in the rat. In the experimental setting, van't Riet et al. found Parietex® to be more susceptible to infection compared to noncoated plain polypropylene mesh [31]. Parietex® also showed significantly less adhesion coverage at 30 days postimplantation and, although there were higher infection rates with Parietex®, mesh incorporation in the abdominal wall was comparable to plain polypropylene mesh.

Expanded polytetrafluoroethylene prostheses with a smooth surface are often employed for laparoscopic and for open incisional hernia repair. These can be used when visceral exposure is unavoidable. If reoperation is required, visceral adhesions to the smooth surface are lysed with relative ease. However, when infection occurs with expanded polytetrafluoroethylene, the prosthesis must be removed to control the infectious process, whereas infection with polypropylene mesh may often be eradicated without excision of the prosthesis.

Biologic prostheses offer a relatively new choice. Preliminary clinical data suggest that they become infected less frequently than synthetics and that healing often occurs, even in the face of infection [32]. These materials are expensive. Long-term results regarding secure ventral abdominal wall hernia repair are still unavailable, although early recurrences have been common with AlloDerm® [33–35]. Biologic prostheses are well tolerated in the abdominal wall, relatively easy to use, and allow for host tissue ingrowth and neovascularization. Kaleya found significantly less adhesion formation and foreign body reaction with porcine dermal collagen compared to polypropylene mesh in a rat model with the prostheses placed intraperitoneally [36]. Seven of the eight animals with porcine dermal collagen prostheses were adhesion-free.

The repair of an abdominal wall defect in the setting of bacterial contamination or infection seems to be an increasing scenario for surgeons worldwide. Infection resistance or tolerance is claimed by the manufacturers of biologic materials for hernia repair. Biologic prostheses and bioresorbable synthetic materials such as Vicryl Mesh® and Dexon Mesh™ (polyglycolic acid) are acceptable choices in the face of contamination. Vicryl Mesh® and Dexon Mesh® solve the immediate problem of bridging the abdominal wall defect, but virtually all of such patients will develop a recurrent hernia. Biologic prostheses have the potential for permanent secure repair, but late followup data are sparse. We noted in the rat that adhesion formation to biologic prostheses is less than to synthetic prostheses, even in the presence of gross infection [32]. In the experimental setting, biologic prostheses have also been shown to reduce adhesion formation when combined with polypropylene

mesh. They will probably prove to reduce the risk of enterocutaneous fistula.

Conclusions

All of the prostheses evaluated induced visceral adhesions. Bare synthetic meshes without an anti-adhesive barrier led to the most extensive adhesion coverage and none were adhesion-free. Biologic prostheses had significantly smaller areas involved. On average, synthetic mesh with an anti-adhesive barrier had areas of adhesion coverage comparable to that of biologics. Both Parietex® and Sepramesh® developed zero adhesions in about half the animals, and Veritas® in one quarter.

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Conflict of interest statement None.

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