SCIENTIFIC PAPER

Evaluation of Composite Mesh for Ventral Hernia Repair

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ABSTRACT

Introduction: Composite mesh prostheses incorporate the properties of multiple materials for ventral hernia repair. This study evaluated a polypropylene/ePTFE composite mesh with a novel internal polydioxanone (PDO) absorbable ring.

Methods: Composite mesh was placed intraperitoneally in 16 pigs through an open laparotomy and explanted at 2, 4, 8, and 12 weeks. Intraabdominal adhesions were measured laparoscopically. Host tissue in-growth was assessed histologically and tensiometrically. Degradation of the internal PDO ring component was also measured tensiometrically. Appropriate statistical tests were used, and $P \leq .05$ indicated significance.

Results: No adhesions were formed in 50% of the grafts explanted at 8 weeks and 25% of grafts explanted at 12 weeks. There were significantly more vascular structures at 8 weeks, 73.5 ± 28, compared with 2 weeks, 6.75 ± 2 ($P \leq .01$). The T-peel force at the mesh-host tissue interface was not significantly different among time points. The absorbable PDO ring underwent complete degradation by 12 weeks.

Conclusions: This composite mesh was associated with minimal intraabdominal adhesions, progressive in-growth of host tissues, and complete degradation of a novel internal PDO ring that aided mesh positioning. This composite hernia mesh showed a favorable performance in a porcine model of open ventral hernia repair.

Key Words: Composite mesh, Ventral hernia repair, Intraabdominal adhesions, Host tissue in-growth.

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INTRODUCTION

Mesh prostheses are an essential component of successful ventral hernia repairs. Mesh is used to produce tension-free repairs, where possible, and offers the best opportunity to restore abdominal wall integrity. Open repairs without mesh are associated with hernia recurrence in 24% to 54% of patients.[1–3] Mesh placement reduces hernia recurrences to 24% to 32% in open repairs[3,4] and 5% to10% in laparoscopic repairs.

Mesh prostheses are composed of biologic materials from human and animal dermis (autoplastic) or synthetic materials (alloplastic). Synthetic mesh prostheses are further divided into 3 groups based on porosity.[5] Type I mesh is macroporous with pore sizes >10 microns, eg, polypropylene. Type II mesh is microporous with pore sizes <10 microns, eg, expanded polytetrafluoroethylene (ePTFE). Type III mesh is a composite structure with both micro- and macroporous components. Polypropylene material causes a local inflammatory response when in contact with host tissues. This combined with its large pore sizes allows for maximal in-growth of connective tissue and blood vessels from the abdominal wall into the mesh material, increasing the strength of ventral hernia repairs. Expanded PTFE is biologically inert and does not cause a host inflammatory response. The submicronic pore sizes of ePTFE mesh materials further impede in-growth of host tissues, thereby, limiting adhesion formation.[6] Composite mesh prostheses are manufactured to strategically position these materials on different surfaces to selectively promote and impede host tissue in-growth to produce a strong ventral hernia repair with minimal adhesions.

Composite mesh prostheses are placed in the intraperitoneal position so that the parietal surface contacts the abdominal wall to promote tissue in-growth, and the visceral surface acts as a long-term barrier for the viscera. Clinical studies have shown that composite mesh materials are associated with short hospital stays, moderate complication rates, low infection rates, and low hernia recurrence rates.[7–9] The clinical success of composite mesh has led to several commercially available materials. The aim of this study was to evaluate a novel composite mesh with an absorbable polydioxanone (PDO) memory ring in a porcine model of open ventral hernia repair.

METHODS

Animals

Sixteen female Yorkshire pigs (35kg to 45kg) were implanted with composite mesh. Animals were randomized for explantation at 2, 4, 8, and 12 weeks. All animal protocols were approved by our medical center's Institutional Animal Care and Use Committee (IACUC) and conformed to Federal Care and Use of Laboratory Animals guidelines.

Mesh Prosthesis

Animals were implanted with Ventrio Hernia Patch (Bard Davol, Inc. Warwick, RI), an oval-shaped composite mesh (11cm x 14cm). This composite hernia patch combines 3 layers of mesh with an absorbable polydioxanone ring that aids in positioning **(Figure 1)**. The parietal surface consists of a double layer of polypropylene. A central opening between the polypropylene layers creates a positioning pocket for the placement of fixation devices. The visceral surface of the mesh is made of ePTFE. The most novel component is an absorbable PDO monofilament incorporated at the periphery of the mesh. This ring allows the flexible hernia patch to return to a flat position against the abdominal wall facilitating optimal positioning. Because this memory function is no longer necessary after the mesh is secured to the abdominal wall, the ring undergoes hydrolysis in vivo and is completely absorbed, decreasing the amount of foreign material in the abdomen.

Surgical Procedures

Following overnight fasting, animals underwent anesthetic induction and endotracheal intubation for surgery. The surgical field was prepped with topical antimicrobial agents and draped to maintain sterility, and midline laparotomy incisions were made. The mesh was placed intraperitoneally and fixed at the periphery with absorbable fasteners at 1-cm intervals. Eight transfascial polydioxanone sutures were placed circumferentially. Each mesh was positioned at the midline, and the overlying fascia was closed primarily with polydioxanone suture in a running fashion. The skin edges were reapproximated with skin staples. A dry, sterile dressing and sulfadiazine cream were placed over the incision. Postoperatively, animals were placed in a recovery area and given appropriate analgesia. Animals had free access to food and water throughout the study duration.

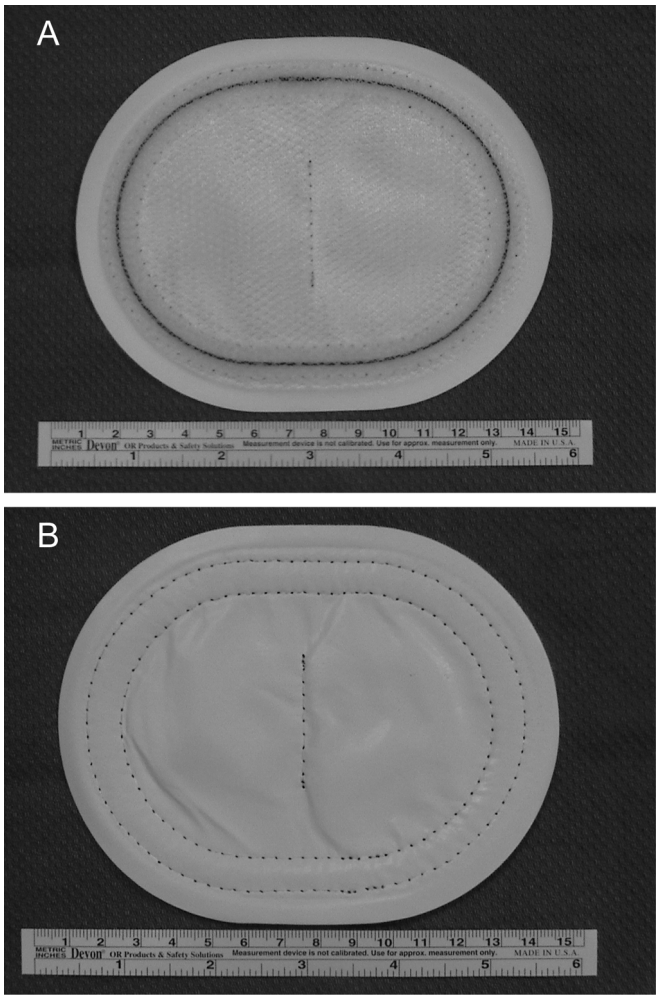

Figure 1. Ventrio Hernia Patch. 1A: polypropylene surface with internalized, absorbable polydioxanone (PDO) ring (arrow), 1B: expanded polytetrafluoroethylene (ePTFE) surface.

Adhesion Scoring

Animals were euthanized at 2, 4, 8, and 12 weeks following mesh implantation (N=4 for each time period). Immediately following euthanasia, animals underwent laparoscopic evaluation of adhesions. An 11-mm trocar was inserted in the right lower quadrant, and pneumoperitoneum was established. A 10-mm, 30° laparoscope was used to directly visualize intraabdominal adhesions. Previously validated quantitative and qualitative scales were used to measure adhesions. The Modified Diamond Scale[10] was used to measure the proportion of mesh covered with adhesions **(Table 1)**, and a scale validated by Garrard and colleagues[11] was used to measure tenacity **(Table 2)**.

Table 1.
Modified Diamond Scale

Score	Percent Adhesion
0	No adhesions
1	<25%
2	25%–50%
3	>50%

Table 2.
Adhesion Tenacity Scale

Score	Description
0	No adhesions
1	Filmy adhesions, easily broken manually
2	Dense adhesions requiring blunt dissection to separate viscera from mesh
3	Very dense adhesions with viscera matted to mesh surface and requiring sharp dissection to separate viscera from mesh

Mesh Contraction

The length and width of each mesh prosthesis was measured at baseline and immediately following explantation. From these measurements, a percentage mesh contracture was calculated for the mesh length, mesh width, and mesh area for each explanted mesh (N=4 for each group). Percentage contracture was calculated by the following formula:

$$\text{Percentage Mesh Contraction} = \frac{(\text{baseline measurement} - \text{explant measurement})}{\text{baseline measurement}} \times 100$$

Histological Evaluation of Cell Types

Immediately following euthanasia, mesh prostheses were explanted by excising each graft along with the overlying full-thickness abdominal wall. Portions of the mesh-abdominal wall complexes explanted from each animal were sectioned, fixed in formalin, and embedded in paraffin or plastic blocks. Replicate 4-μm to 6-μm sections were cut and stained with hematoxylin and eosin (H&E) and Masson's trichrome. Slides from each animal were divided into quadrants, and 3 fields from each quadrant were selected for cell counting. Twelve high-power fields (40X magnification) were evaluated for each animal, and group means were calculated for each time point (N=48 high power fields per group). Each field was independently scored for the presence of inflammatory cells, vascular structures, and fibroblasts by 2 observers who were blinded to specimen group assignments.

Tensiometric Evaluation of Mesh-Tissue Interface

Immediately following explantation, mesh-abdominal wall specimens were placed in normal saline. Skin and soft tissues were removed, leaving a thin, connective tissue lamina on the polypropylene surface of the mesh. Fixation constructs were removed. The degree of polypropylene mesh incorporation into the abdominal wall was assessed by measuring the force required to separate the connective tissue lamina from the underlying mesh (T-peel force). Specimens were cut into 2-cm x 7-cm strips, and T-peel forces were measured at a constant displacement of 20mm per minute. Explanted mesh was tested at 2 weeks (N=23), 4 weeks (N=20), 8 weeks (N=17), and 12 weeks (N=20) following implantation.

Evaluation of Internal PDO Ring

The mechanical properties of the absorbable PDO ring component of each mesh were evaluated in triplicates at baseline and 2, 4, 8, and 12 weeks (N=12 specimens for each group). These longitudinal measurements were used to quantify the amount of PDO ring degradation. The rings were dissected from the explanted mesh and maintained in normal saline before testing. Ultimate tensile strength was calculated from the peak load and initial diameter for each ring sample. Ring material from nonimplanted mesh was also tested for baseline values.

Data Analysis

Data are presented as mean values with standard deviations or proportions. Kruskal-Wallis tests were used for ordinal data, and ANOVA followed by Tukey post hoc tests were used for interval data. All tests were 2-tailed, and significance was considered $P \leq .05$.

RESULTS

Laparoscopic Inspection

There were no operative or postoperative complications. All animals survived to the designated endpoints by group (2, 4, 8, and 12 weeks) and were healthy throughout the study. Laparoscopic inspections showed that composite mesh prostheses were securely positioned and flat against the abdominal wall with no exposure of the parietal mesh surface.

Adhesion Scoring

Quantitative and qualitative measurements of intraabdominal adhesions were performed using the Modified Diamond Scale and a tenacity scale, respectively. The overall mean Diamond score for all groups was 0.63±0.62 (N=16), and the overall mean tenacity score was 1.94±1.0 (N=16). Diamond and tenacity scores were not statistically different among groups (P=.38 and P=.51, respectively). All groups included animals with no adhesions: 2 week (25%), 4 week (75%), 8 week (50%), and 12 week (25%). Of the animals that developed adhesions, all measured <25%, and most were filmy omental attachments. See **Tables 3** and **4** and **Figure 2** for adhesion scores.

Mesh Contraction

The width, length, and surface area of explanted mesh were compared with baseline measurements, and percentage of contraction for these dimensions was calculated for each time point. The percentage surface area contraction was 4% at 2 weeks, 19% at 4 weeks, 16% at 8 weeks, and 19% at 12 weeks. Mesh length contraction was slightly greater than width contraction at 2 weeks, and width contraction was greater than length contraction at 4, 8, and 12 weeks following implantation. See **Figure 3** for mesh contraction results.

Histological Evaluation of Cell Types

The tissue architecture was evaluated by light microscopy at 40X magnification. At 2 weeks, there was a preponderance of lymphocytes and other inflammatory cells with disorganized collagen fibers. By 12 weeks, there were fewer inflammatory cells, and the tissues had undergone marked remodeling with well-organized collagen fibers. The numbers of cells per high power field (CHPF) were also counted. Neutrophils and giant cells were counted in quantities too low for comparisons across groups. There were 6.75±2 vascular structures at 2 weeks, and the maximum number of structures was 73.5±28 at 8 weeks (P<.01). Fibroblasts measured 209.75±20 CHPF at 2 weeks and a maximum of 288±24 CHPF at 12 weeks (P=.056). Macrophages were counted as 141±42 CHPF at 2 weeks and a maximum of 224.25±116 CHPF (P=.26). See **Figures 4, 5**, and **6** for histological data.

Table 3.
Quantitative Adhesion Results

	Diamond Score	2 Wk N (%)	4 Wk N (%)	8 Wk N (%)	12 Wk N (%)
None	0	1 (25)	3 (75)	2 (50)	1 (25)
<25%	1	3 (75)	1 (25)	2 (50)	2 (50)
25–50%	2	0	0	0	1 (25)
>50%	3	0	0	0	0

Table 4.
Qualitative Adhesion Results

	Tenacity Score	2 Wk N (%)	4 Wk N (%)	8 Wk % N (%)	12 Wk N (%)
None	1	1 (25)	3 (75)	2 (50)	1 (25)
Filmy	2	3 (75)	0	1 (25)	0
Dense	3	0	1 (25)	0	3 (75)
Very Dense	4	0	0	1 (25)	0

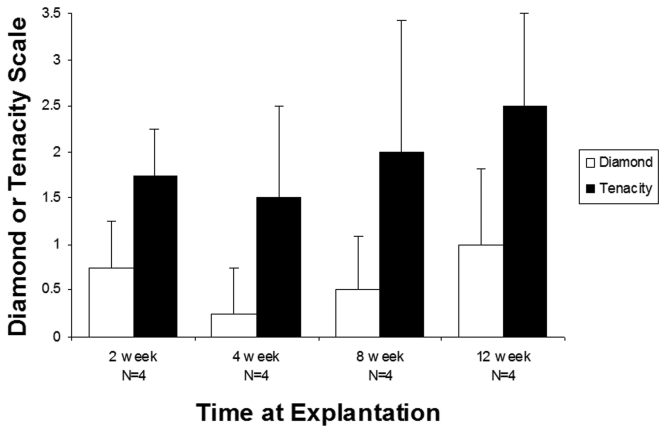

Figure 2. Graph demonstrating mean adhesion scores over time.

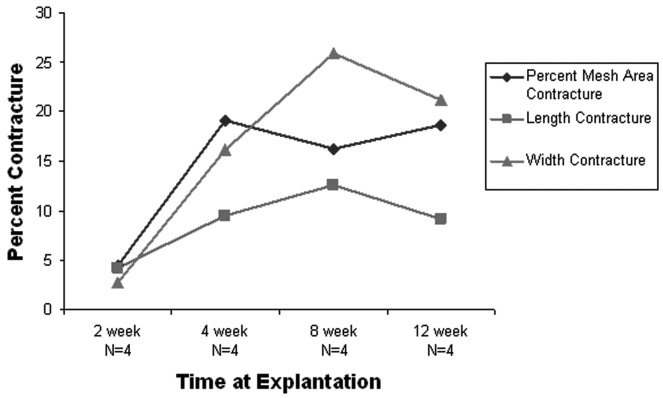

Figure 3. Graph demonstrating the percent mesh contraction over time.

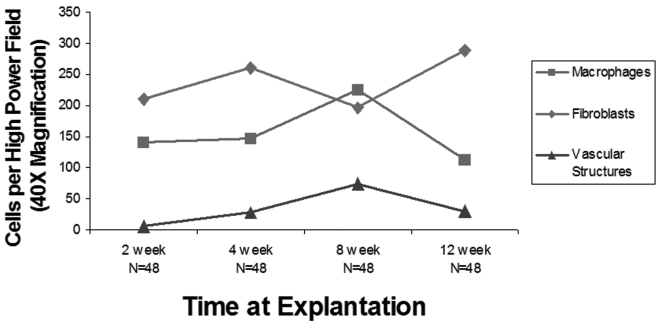

Figure 4. Graph demonstrating host cellular response to mesh over time.

Tensiometric Evaluation Mesh-Tissue Interface

The force required (T-peel force) to separate host connective tissue lamina from the mesh was measured to assess the in-growth of host tissues into the mesh. T-peel force was highest at 2 weeks, 9.13±3 Newtons, and lowest at 8 weeks, 4.76±2 Newtons. There was no significant difference in T-peel forces among the groups (P=.29). See **Figure 7** for T-peel force measurements.

Evaluation of Internal PDO Ring

The absorbable ring component of the composite mesh underwent tensiometric testing to assess ring degradation. The ultimate tensile strength was calculated from the peak load and an initial ring diameter. The ultimate tensile strength at baseline was 367±5 Mpa and progressively decreased in each group following explantation: 275.2±49 Mpa at 2 weeks, 87±18 Mpa at 4 weeks, and 9.7±7 Mpa at 8 weeks (P<.001). The strain and modulus were measured and followed similar trends. All mechanical test samples at 12 weeks had degraded such that no mechanical tests could be successfully completed. The percentage of degradation of the PDO ring compared to baseline measurements was 25% at 2 weeks, 76.2% at 4 weeks, 97.4% at 8 weeks, and 100% at 12 weeks. See **Figure 8** for measurements of the internal PDO ring.

DISCUSSION

Our preclinical, observational study evaluated a new composite mesh for soft tissue reconstruction, the Ventrio

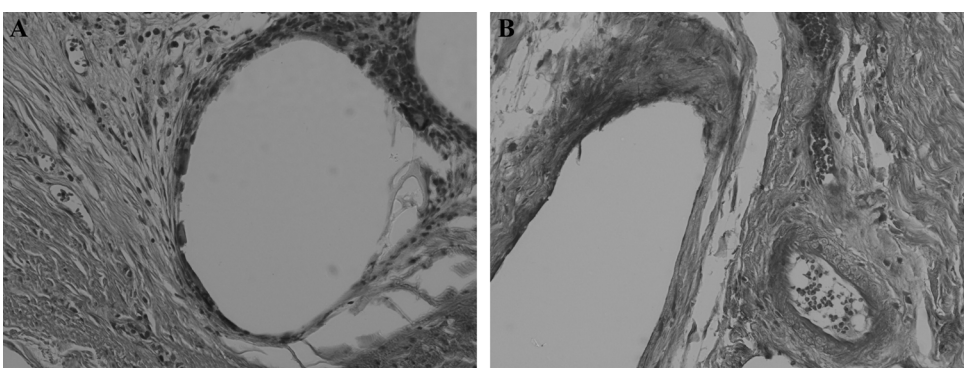

Figure 5. Histological preparation of explanted mesh at 2 weeks (20X magnification). 5A: H&E stain, 5B: Masson's trichrome stain. Note the prominence of inflammatory cells and disordered collagen fibers.

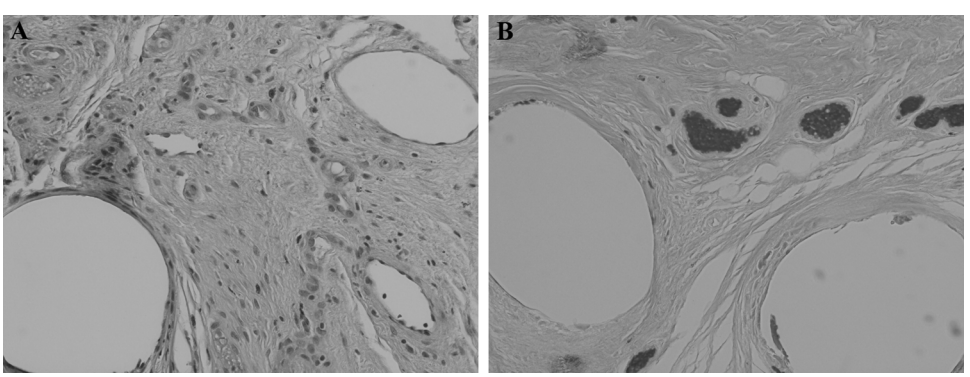

Figure 6. Histological preparation of explanted mesh at 12 weeks (20X magnification). 6A: H&E stain, 6B: Masson's trichrome stain. Note the decrease in inflammatory cells and the increased deposition of organized collagen fibers and vascular structures.

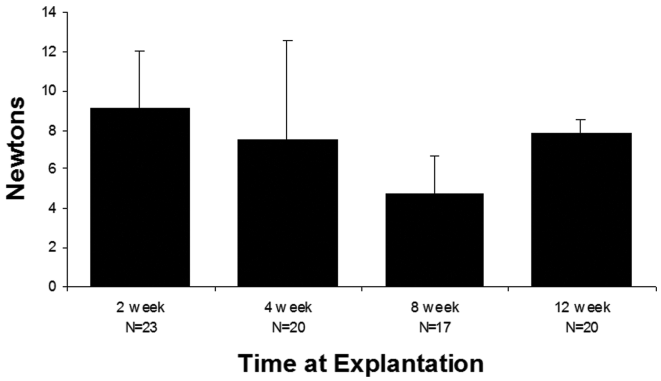

Figure 7. Graph demonstrating the T-peel force of mesh-tissue interface over time.

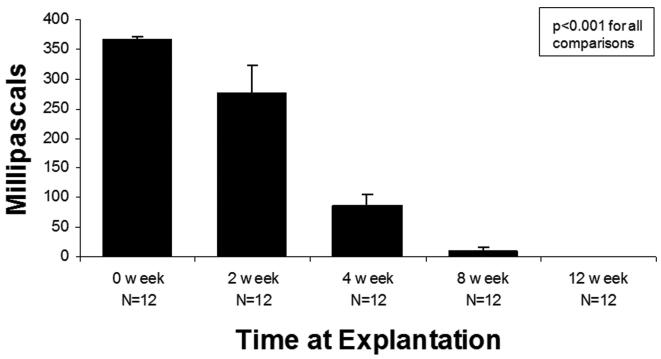

Figure 8. Graph demonstrating the tensile strength of absorbable PDO ring over time.

Hernia Patch (Bard Davol, Inc. Warwick, RI). Adhesions were absent in some animals at each time point. Animals that developed adhesions were found to have thin, filmy omental attachments. Histological evaluation showed progressive host tissue in-growth into the mesh with increased vascular structures and fibroblasts at 8 weeks and 12 weeks compared to earlier time points. Two features were found to promote easy handling of the mesh and proper placement in the intraperitoneal space. The positioning pocket created by the polypropylene bi-layer facilitated appropriate mesh fixation with fasteners. The internal PDO ring enabled the mesh to maintain a flat orientation during placement. This PDO ring also underwent complete degradation by 12 weeks.

Ventral hernias are common complications following open laparotomies with a reported incidence ranging from 2% to 20%.[1,12–15] Mesh prostheses offer the lowest rate of hernia recurrence. There are many mesh products available for use during ventral hernia repairs; however, there is no consensus regarding the optimal graft because of the wide variability in patients as well as hernias. The ideal mesh material provides a strong repair with minimal adverse effects resulting from the foreign material within the abdomen. The use of composite mesh prostheses placed intraperitoneally seeks to accomplish aggressive host tissue response at the parietal surface to strengthen the repair while minimizing adhesions caused by contact on the visceral surface.

The composite mesh evaluated in this study incorporates 3 layers of mesh material with an absorbable ring to maximize strength for the hernia repair. Two layers of polypropylene material make up the parietal surface. The macroporosity of polypropylene is shown to promote in-growth of host tissue within the mesh, which adds to the longevity of strength for the hernia repair.[8,9] This study evaluated this property mechanically by measuring the force required to separate host connective tissue from the mesh (T-peel force) and histologically by assessing cell types in the mesh following implantation. The T-peel force was highest at 2 weeks, indicating a strong initial mesh-abdominal association. The T-peel force was relatively weakest at 8 weeks but increased again by 12 weeks. The T-peel force at 2 weeks is likely a result of an early host inflammatory response. The relatively lower T-peel force at 8 weeks may be indicative of a window phase in which the acute inflammatory response has subsided and the process of remodeling has begun. This theory is supported by the progressive increase of vascular structures and well-organized fibroblasts at 12 weeks **(Figures 5** and **6)**. As the remodeling process continues (beyond 12 weeks), the T-peel force would likely exceed values observed at 2 weeks.

The visceral surface of the composite mesh was made of ePTFE, a microporous material that inhibits tissue attachment and limits the formation of intraabdominal adhesions between viscera and the mesh surface.[8,9] Results of this study show that many animals in each group formed no adhesions at all, including 75% at 4 weeks and 50% at 8 weeks. Of animals that formed adhesions, many of them were filmy omental adhesions that were easily broken with blunt dissection. Animal studies have reported Modified Diamond scores of 0.8 to 1.6 associated with ePTFE and polypropylene mesh materials.[16] The mean Modified Diamond score for the current study was lower at 0.63 ± 0.62.

The composite mesh evaluated in this study was most innovative in the components designed to ensure appropriate placement within the intraperitoneal cavity and adequate fixation of the mesh to the abdominal wall. The positioning pocket created by the polypropylene bi-layer

helped to ensure adequate fixation at the mesh periphery. The absorbable PDO ring component ensured the mesh maintained a flat orientation against the abdominal wall during placement. The ring was also completely degraded by 12 weeks, leaving less foreign material in the abdomen and no risk for long-term complications caused by this component. These features are significant advances in composite mesh design and aid in adequate mesh placement and fixation, both of which are required for successful hernia repairs.

Contraction of mesh prostheses is well documented, and the cause is contraction of collagen and connective tissue as host tissues become incorporated in the woven mesh interface. Radiologic measurements have shown 20% mesh contraction 10 months after implantation in patients.[6] Gonzalez and colleagues[17] examined mesh contraction 3 months following implantation in a porcine model. Contraction of polyester mesh was between 5% and 24%, and contraction of polypropylene mesh was between 15% and 65%. Our data show a mean 19% mesh area contraction at 12 weeks. The structure of the composite hernia patch may be responsible for this relatively low contraction profile compared to that of other prostheses.

CONCLUSION

Ventrio Hernia Patch incorporates 3 layers of mesh material with an absorbable PDO ring. Each layer performs a unique functional role to increase the strength of ventral hernia repairs while minimizing adhesion formation and mesh contraction. This study showed that the visceral ePTFE layer was associated with minimal adhesion formation. The parietal polypropylene layers contributed to aggressive in-growth of host tissues and provided a positioning pocket that aided in mesh fixation. The PDO ring aided in mesh placement and was completely absorbed by 12 weeks. This study provides sound evidence to support prospective clinical trials examining this composite mesh in clinical settings.

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