Bioprosthetic Tissue Matrices in Complex Abdominal Wall Reconstruction

Justin M. Broyles, MD*
Nicholas B. Abt, BS*
Justin M. Sacks, MD, FACS*
Charles E. Butler, MD, FACS†

Background: Complex abdominal defects are difficult problems encountered by surgeons in multiple specialties. Although current evidence supports the primary repair of these defects with mesh reinforcement, it is unclear which mesh is superior for any given clinical scenario. The purpose of this review was to explore the characteristics of and clinical relevance behind bioprosthetic tissue matrices in an effort to better clarify their role in abdominal wall reconstruction.

Methods: We reviewed the peer-reviewed literature on the use of bioprosthetic mesh in human subjects. Basic science articles and large retrospective and prospective reviews were included in author's analysis. The clinical performance and characteristics of 13 bioprosthetic tissue matrices were evaluated.

Results: The majority of the products evaluated perform well in contaminated fields, where the risk of wound-healing difficulties is high. Clinical outcomes, which included infection, reherniation, and bulge formation, were variable, and the majority of the studies had a mean follow-up of less than 24 months.

Conclusions: Although bioprosthetic matrix has a multitude of indications within the growing field of abdominal wall reconstruction, the functionality, regenerative capacity, and long-term fate of these products have yet to be fully established. Furthermore, the clinical performance, indications, and contraindications for each type of matrix need to be fully evaluated in long-term outcome studies. *(Plast Reconstr Surg Glob Open 2013;1:e91; doi: 10.1097/GOX.0000000000000036; Published online 27 December 2013)*

Complex abdominal wall defects are challenging problems requiring a multidisciplinary approach to obtain satisfactory results. Often, the surgeon is presented with a patient who has endured numerous operations that have left the skin and fascia attenuated. Advances in surgical techniques such as component separation and tissue expansion have addressed the need for soft tissue coverage, but reinforcement of the fascia remains a problem. Repairs that utilize mesh for fascial reconstruction have hernia recurrence rates at 10-year follow-up that are roughly 50% lower than those for primary suture repair.[1] However, patient selection and mesh composition are still areas of uncertainty in this rapidly evolving field.

Ventral hernia repair by primary suture alone is associated with unacceptable recurrence rates.[2] In clean cases, prosthetic mesh reinforcement of a fas-

cial repair is the gold standard. In heavily contaminated wounds, prosthetic mesh is often considered to be contraindicated owing to the high risk of infection. Additionally, prosthetic mesh is associated with erosion into the abdominal viscera, adhesions, and chronic pain.[3,4] In these wounds, a bioprosthetic tissue matrix (BTM) is an alternative to prosthetic mesh owing to the material's ability to tolerate cutaneous exposure and withstand placement into a contaminated defect.

Commercially available BTMs currently come from 5 different sources: human dermis, porcine dermis, porcine small intestinal submucosa, bovine dermis, and bovine pericardium (Table 1). Once the tissues are harvested, they undergo a decellularization process aimed at preventing an immune response. Some BTMs are dehydrated to extend their shelf life and reduce the loss of growth factors during storage and others are subjected to additional collagen cross-linking. Given the plethora of available products and the limited clinical experience with them, additional clarification is required to make sound clinical decisions as to which product is superior in a given circumstance. In this review, we evaluated available literature for large retrospective and prospective trials to identify the key features of 13 different BTMs. We compared the clinical applications and outcomes of these products to further define indications for their use in this rapidly changing field.

CHARACTERISTICS OF BIOPROSTHETIC MATRICES

Chemical Collagen Cross-linking
Collagen cross-linking was introduced initially to control collagen breakdown and to maintain the structural integrity of the graft. In defects that include bacterial contamination, the cross-linking may confer resistance against bacterial collagenases.[5] The use of chemical agents, such as hexamethylene diisocyanate, hinders the ability of collagenases to break down the matrix.[6] However, chemicals not completely removed could result in cytotoxicity and inflammation. Animal studies utilizing a ventral hernia repair model in guinea pigs demonstrated that cross-linking of porcine BTM resulted in a higher grade of intra-abdominal adhesions, lower degree of vascular infiltration, and decreased mechanical strength at the matrix-fascial interface.[7]

Numerous human studies have examined how the body responds to cross-linking. Liang et al[8] demonstrated that non-cross-linked BTMs were absorbed before new collagen deposition by fibroblasts could occur. de Castro Brás et al[9] observed more cellular penetration of non-cross-linked porcine BTMs than cross-linked porcine BTMs at 3 and 6 months postimplantation. However, at 12 months, both demonstrated equal implant integration, with the cross-linked BTM exhibiting greater cellular density. These studies demonstrate that there is a delicate balance in extracellular cross-linking. While cross-linking confers mechanical strength and resistance to degradation, both human and animal studies demonstrate that BTMs that are highly cross-linked behave more like prosthetic meshes than BTMs as evidenced by limited cell and vascular infiltration and propensity for encapsulation.[7]

Inflammatory and Foreign Body Response
Prolonged inflammatory response at the matrix implantation site seems to hinder tissue integration, promote scarring, and permit encapsulation. This reaction is carried out by macrophages and monocytes through the use of various cytokines and interleukins. A human study evaluating the host reaction to porcine BTM demonstrated that cross-linked products such as Collamend (Davol, Warwick, R.I.) and Permacol (Covidien, Norwalk, Conn.) elicited a

Table 1. Summary of Bioprosthetic Tissue Matrices

Proprietary Name	Manufacturer	Donor	Material	Cross-linked
Surgisis	Cook Medical	Porcine	SIS	No
Biodesign	Cook Medical	Porcine	SIS	No
Permacol	Tissue Science Laboratories	Porcine	Dermis	Yes
Collamend	Bard	Porcine	Dermis	Yes
Strattice	LifeCell	Porcine	Dermis	No
Xenmatrix	Bard	Porcine	Dermis	No
Tutopatch	Tutogen	Bovine	Pericardium	No
Veritas	Synovis	Bovine	Pericardium	No
PeriGuard	Synovis	Bovine	Pericardium	No
Surgimend	TEI Bioscience	Bovine	Dermis	No
AlloDerm	LifeCell	Human	Dermis	No
Flex HD	Ethicon	Human	Dermis	No
AlloMax	Bard	Human	Dermis	No

SIS, small intestine submucosa.

significantly greater amount of macrophages and inflammatory cytokines than non-cross-linked matrices such as Strattice (LifeCell Corporation, Branchburg, N.J.) or Surgisis (Cook Medical, Bloomington, Ind.). Furthermore, Strattice had the lowest inflammatory cytokine profile of the 4 porcine BTMs.[10]

Evaluation of 3 non-cross-linked human BTMs in a similar experimental model demonstrated that Flex HD (Ethicon, Sommerville, N.J.) had the greatest inflammatory response, as measured by macrophage induction and cytokine expression analysis.[11] AlloMax (Bard, Warwick, R.I.) and Allo-Derm (LifeCell Corporation, Branchburg, N.J.) had lower levels of inflammatory markers, with AlloDerm possessing the most benign inflammatory profile. Petter-Puchner et al[12] demonstrated that intraperitoneal implantation of a porcine BTM produced a macrophage-driven response exhibiting persistent granulomatous inflammation. Additionally, clinical models have demonstrated that the inflammatory process abates after a cross-linked porcine BTM fully integrates into the surrounding tissue. As evidenced in these studies, cross-linking of BTMs tends to increase the foreign body response; however, the inflammatory reaction does not predict long-term clinical outcomes.

Tensile Strength and Revascularization Capacity

During the healing process, the BTM must be able to withstand the physiological forces placed upon it until full integration. Mulier et al[13] reported that a cross-linked porcine BTM retained more of its tensile strength than the equivalent non-cross-linked matrix at 3, 6, and 12 months postoperatively. The thickness of the explanted cross-linked graft was also reported to be similar to its initial thickness, whereas the non-cross-linked matrix had a significant reduction in thickness. Gaertner et al[14] suggested that non-cross-linked implants would be insufficient for abdominal wall reconstruction because of their loss of tensile strength over a 6-month period.

Remodeling and revascularization of the implanted BTM is the final step in successful reconstruction. BTMs that do not undergo remodeling act as permanent foreign bodies. Deeken et al[15] reported that expeditious remodeling was seen with non-cross-linked matrices; however, this did not lead to improved clinical outcomes in long-term follow-up. By contrast, Collamend, a heavily cross-linked BTM, was not absorbed at the implantation site and exhibited no signs of remodeling at 6 months postimplantation.[16] Animal studies have demonstrated that the extensive cross-linking seen in Collamend is associated with decreased neovascularization, decreased cellular ingrowth, and a higher risk of encapsulation of the matrix, displaying behaviors that are more similar to prosthetic meshes than BTMs.[7] It is clear that remodeling of these BTMs contributes to their ability to resist infection and tolerate contamination; however, the optimal degree of cross-linking has yet to be elucidated.

GENERAL TYPES OF TISSUE MATRICES

Porcine Xenografts

The 6 porcine xenografts developed for reconstructive use vary according to their composition and processing techniques, which can affect outcomes. All but 2 of these products are derived from dermis, with the remaining products derived from small intestine submucosa. Two of the 6 products are terminally cross-linked.

Surgisis/Biodesign. Surgisis, a non-cross-linked BTM derived from porcine small intestine submucosa, was first used in 1999. The product was reintroduced in 2008 as Biodesign (Cook Medical, Bloomington, Ind.) after undergoing several modifications. This submucosa is harvested between the outer muscular wall of the small intestine and the underlying muscularis mucosa.[17] Surgisis was evaluated in the only level-one, prospective, randomized trial of a BTM for paraesophageal repair; however, the results were discouraging with 59% of patients having recurrent hernias at a mean follow-up of 58 months.[18]

Franklin and coworkers[19,20] published articles on laparoscopic ventral hernia repair using Surgisis, which included 81 cases in both clean and contaminated wounds. They reported a low recurrence rate of 3.7% at the 5-year follow-up. Ueno et al[21] reported using Surgisis in 18 cases of complicated open ventral hernia repairs. Half of the procedures were done in a contaminated field, and the matrix was employed as a bridged repair. A 50% complication rate was reported, along with a 10% seroma rate. Helton et al[22] evaluated Surgisis in 53 ventral hernia repairs, finding a 41% overall complication rate, including one third of patients requiring reoperation. Surgisis and Biodesign outcomes seem to be dependent on the level of surgical field contamination. It seems to perform well in clean fields, but caution is required in contaminated wounds to prevent complications.

Permacol. Permacol is a cross-linked porcine BTM that is used in plastic and gynecologic surgery procedures. Cobb and Shaffer[17,23] described 60 patients who underwent ventral hernia repair with Permacol. Ninety-three percent of the repairs were done in noncontaminated fields. A 7% recurrence rate and a 4% wound complication

rate were reported at 14 months' follow-up. Hsu et al[24] published 28 cases of abdominal wall reconstruction, noting an 11% recurrence rate at a mean follow-up of 16 months. Finally, 2 case reports of bridged hernia repair with colostomies in a clean-contaminated field reported no recurrences after 1 year.[25,26] Only 15% of reported cases using Permacol in abdominal wall reconstruction have been performed in contaminated fields, raising concerns about the durability of the product in the setting of contamination. Based on the literature, Permacol seems to work well in clean cases. The effects of cross-linking in the setting of contamination are less clear based on available evidence.

Collamend. Collamend, a heavily cross-linked porcine BTM, was first used in 2006. Animal studies demonstrate that this extensive cross-linking promotes adhesion formation and decreases neovascularization.[7] Chavarriaga et al[27] reaffirmed these results in a report on Collamend in abdominal wall reconstruction. Eighteen patients underwent abdominal wall reconstruction, with a 44% recurrence rate at a mean follow-up of 7 months. The infection rate of the graft was 38%, and all patients required explantation due to encapsulation. Thus, Collamend should likely be avoided in contaminated wounds because of its propensity for infection and encapsulation. Collamend is no longer commercially available for abdominal wall reconstruction.

Strattice. Strattice is derived from porcine dermis and is not cross-linked. The galactose-α(1,3)-galactose antigen, which is the major cause of inflammation associated with acellular xenografts, is enzymatically removed, thereby decreasing antigenicity.[28,29] Animal studies demonstrate that ventral hernia repairs with Strattice result in decreased adhesions, increased cell trafficking, and increased tensile strength.[7] The first prospective, multi-institutional trial of a BTM for abdominal wall reconstruction was performed with Strattice.[30] The study included 80 patients who underwent single-stage repairs using Strattice in contaminated defects. Two thirds of the patients experienced surgical site wound morbidity, but the BTM did not require removal in any case. Hernia recurrence rates approached 19% at 1-year follow-up. Importantly, bridged repairs resulted in a hernia recurrence rate of 38%, whereas reinforced repairs had a 14% recurrence rate.

Rosen et al[31] described a 12-patient series of midline hernia repairs using Strattice. There was an 18% hernia recurrence rate after 1 year of follow-up. Finally, Clemens et al[32] retrospectively analyzed 69 cancer patients who underwent abdominal wall reconstruction with a mean follow-up time of 21 months. Strattice was placed in the inlay position, and bridged repairs were excluded from the analysis. This study demonstrated low hernia and bulge recurrence rates of 2.9% and 7.2%, respectively. The clinical efficacy of Strattice in abdominal wall reconstruction has demonstrated moderate success in several studies; however, long-term outcomes are currently lacking in the literature and need to be evaluated in the future.

Xenmatrix. Xenmatrix (Bard, Warwick, R.I.), another non-cross-linked porcine BTM, was approved in 2003. Pomahac and Aflaki[33] published a retrospective study of 16 trauma patients who underwent several different reconstructive techniques. A 7% recurrence rate was noted after a 16-month follow-up period. Byrnes et al[34] described 57 patients with large incisional hernias. All repairs were done in a clean environment, with no reported defect contamination. Hernia recurrence was reported at 8% with a 30-month follow-up. This recurrence rate increased to 55% when Xenmatrix was used as a bridged repair. On the basis of this study, Xenmatrix seems to function moderately well in clean environments. However, the practicality of this product is difficult to ascertain because there have been only 2 small, retrospective studies in the literature evaluating its efficacy.

Bovine Xenografts

Four bovine xenografts are currently available for reconstructive use. Three are derived from bovine pericardium and one from bovine dermis. None of the available products are terminally cross-linked.

Tutopatch. Tutopatch (Tutogen Medical, Alachua, Fla.) is a non-cross-linked bovine pericardial matrix that was approved in 2000. Only one report has been published evaluating its efficacy. van Tuil et al[35] reported on 29 neonates who underwent reconstruction utilizing various techniques to repair gastroschises and omphaloceles. These techniques included primary repair in 5 neonates, onlay reinforcement in 9 neonates, and bridged repair in the remaining 15 neonates. No recurrences were reported at the 2-year follow-up. With no recurrences, Tutopatch seems suitable for abdominal wall reconstruction in neonates; however, more clinical data are needed to determine its broader applicability.

Veritas. Veritas (Synovis Surgical Innovations, St. Paul, Minn.) is another non-cross-linked bovine pericardial tissue matrix. Limpert et al[36] reported 26 patients

who underwent abdominal wall reconstruction. The hernia recurrence rate was 19% with a mean follow-up of 22 months. From this limited evidence, it is difficult to determine whether this product can be used efficaciously. Future studies with more patients are needed to evaluate its performance.

PeriGuard. Periguard (Synovis Surgical Innovations, St. Paul, Minn.) is a bovine pericardial BTM developed for use in 1992. To date, there is no peer-reviewed literature in humans describing its outcomes.

Surgimend. Surgimend (TEI Biosciences, Boston, Mass.) is a terminally sterilized BTM processed from fetal bovine dermis. Proponents of the BTM claim that the increased amount of type III collagen and inherit tensile strength of the material make it clinically superior. A retrospective study from Janfaza et al[37] reported 23 ventral hernia repairs with a minimum 90-day follow-up. Forty-eight percent of the cases were contaminated and the recurrent hernia rate was 5%. A larger study by Clemens et al[32] analyzed 51 cancer patients undergoing abdominal wall reconstruction with a mean follow-up time of 21 months. This study demonstrated low hernia and bulge recurrence rates of 3.9% and 0%, respectively. On the basis of these studies, this BTM seems to be promising. However, future studies with longer follow-up and greater numbers of patients will dictate what role this product will ultimately play in abdominal wall reconstruction.

Human Acellular Dermal Matrix

Human acellular dermal matrix, obtained from cadaveric dermis, was introduced in 2003. Currently, there are 3 products available, and none are cross-linked. The ability of human acellular dermal matrix to resist and clear infection is attributed to the early revascularization of these BTMs.[38,39]

AlloDerm. AlloDerm is a cadaveric, non-cross-linked acellular dermal matrix that has been evaluated extensively in abdominal wall reconstruction. Three large, retrospective studies described the use of AlloDerm for abdominal wall reconstruction with a total of 171 patients.[38,40,41] Preoperative wound contamination was present in 97% of the patients. High wound complication rates, including graft exposure, were reported postoperatively. BTM explantation occurred in only 4% of patients, and a majority of the infections were treated with local wound care.

AlloDerm performs well in the setting of contamination, although the optimal position of mesh placement is still uncertain. Jin et al[42] evaluated how various placement techniques (ie, reinforced repairs vs bridged repairs) affected long-term outcomes. In this study, they demonstrated an 80% recurrence rate for the bridged repairs, with a 20% recurrence rate for the reinforced repairs at 2 years' follow-up.

A review of cases using AlloDerm from the senior author's institution evaluated 46 cancer patients with abdominal defects repaired with inlay AlloDerm.[43] Sixty-one percent of the defects were grossly contaminated. Bridged and reinforced repairs were done in 39% and 61% of patients, respectively. A significantly lower bulge rate between fascial reinforcement (7%) and bridged repair (33%) was witnessed. Hernias arose in 10 patients (22%), with a mean development time of 38 months. To date, this is the only long-term study evaluating AlloDerm in abdominal wall reconstruction with an acceptable mean follow-up of 3 years. The observation that the mean time to bulge and hernia formation was more than 3 years indicates that studies with follow-up of less than 3 years may be insufficient to evaluate long-term outcomes.

AlloDerm is the most studied BTM available today. It seems that this BTM performs well in the presence of contamination and cutaneous exposure. However, there are concerns relating to the long-term performance of the BTM, particularly when fascial closure cannot be achieved (reinforced repair) and a bridged repair is required. For this reason, the use of AlloDerm in abdominal wall reconstruction is often avoided owing to the unacceptably high incidence of bulges in bridged repairs.

Flex HD. Flex HD is a non-cross-linked acellular dermal matrix derived from humans. There is only one, small retrospective trial demonstrating its use in human subjects.[37] In this study, 12 patients were evaluated retrospectively for a minimum of 90 days after ventral hernia repair. Fifty-three percent of these cases were performed in contaminated fields. At 90 days' follow-up, 33% of the patients had recurrent hernias. For this reason, the use of Flex HD in abdominal wall reconstruction should be considered cautiously.

AlloMax. AlloMax is non-cross-linked BTM derived from human dermis. To date, there is no peer-reviewed literature in humans describing the product's efficacy in abdominal wall reconstruction.

Future Directions

Future innovations in BTM development will incorporate techniques from both regenerative medicine and biomedical engineering. Novel BTMs

could improve upon current technology through improvement of matrix integration and tensile strength. Studies in animal models demonstrate that angiogenic factors such as vascular endothelial growth factor can be incorporated into BTMs to increase angiogenesis and cell trafficking.[44] Additionally, the use of stem cell therapy to engineer skeletal muscle can provide scaffolding to repair large abdominal defects.[45] Finally, BTMs can be seeded with adipose-derived stem cells to increase both cellular and vascular infiltration.[46] Future work will aim to clarify tissue-derived stem cell roles in promoting healing and vascular ingrowth and promote translational research into the clinical arena.

CONCLUSIONS

The past 20 years has seen an explosion of BTMs available for surgical use. Despite their similarities, it is clear that no 2 products are identical and that certain characteristics may permit superior performance in different clinical scenarios. Future studies should aim to clarify individual roles for each product using evidence-based medicine in an effort to improve patient outcomes.

Charles E. Butler, MD, FACS
Department of Plastic and Reconstructive Surgery
The University of Texas MD Anderson Cancer Center
1515 Holcombe Boulevard
Unit 1488, Houston, TX 77030
E-mail: cbutler@mdanderson.org

REFERENCES

1. Burger JW, Luijendijk RW, Hop WC, et al. Long-term follow-up of a randomized controlled trial of suture versus mesh repair of incisional hernia. *Ann Surg.* 2004;240:578–583; discussion 583–585.
2. Bellows CF, Smith A, Malsbury J, et al. Repair of incisional hernias with biological prosthesis: a systematic review of current evidence. *Am J Surg.* 2013;205:85–101.
3. Godden AR, Daniels IR, Giordano P. The role of biologic meshes in abdominal wall reconstruction. *Colorectal Dis.* 2012;14(Suppl 3):7–11.
4. Butler CE, Langstein HN, Kronowitz SJ. Pelvic, abdominal, and chest wall reconstruction with AlloDerm in patients at increased risk for mesh-related complications. *Plast Reconstr Surg.* 2005;116:1263–1275; discussion 1276–1277.
5. Novitsky YW, Rosen MJ. The biology of biologics: basic science and clinical concepts. *Plast Reconstr Surg.* 2012;130(5 Suppl 2):9S–17S.
6. Smart NJ, Bloor S. Durability of biologic implants for use in hernia repair: a review. *Surg Innov.* 2012;19:221–229.
7. Butler CE, Burns NK, Campbell KT, et al. Comparison of cross-linked and non-cross-linked porcine acellular dermal matrices for ventral hernia repair. *J Am Coll Surg.* 2010;211:368–376.
8. Liang HC, Chang Y, Hsu CK, et al. Effects of crosslinking degree of an acellular biological tissue on its tissue regeneration pattern. *Biomaterials* 2004;25:3541–3552.
9. de Castro Brás LE, Proffitt JL, Bloor S, et al. Effect of crosslinking on the performance of a collagen-derived biomaterial as an implant for soft tissue repair: a rodent model. *J Biomed Mater Res B Appl Biomater.* 2010;95:239–249.
10. Orenstein SB, Qiao Y, Klueh U, et al. Activation of human mononuclear cells by porcine biologic meshes in vitro. *Hernia* 2010;14:401–407.
11. Orenstein SB, Qiao Y, Kaur M, et al. Human monocyte activation by biologic and biodegradable meshes in vitro. *Surg Endosc.* 2010;24:805–811.
12. Petter-Puchner AH, Fortelny RH, Silic K, et al. Biologic hernia implants in experimental intraperitoneal onlay mesh plasty repair: the impact of proprietary collagen processing methods and fibrin sealant application on tissue integration. *Surg Endosc.* 2011;25:3245–3252.
13. Mulier KE, Nguyen AH, Delaney JP, et al. Comparison of Permacol™ and Strattice™ for the repair of abdominal wall defects. *Hernia* 2011;15:315–319.
14. Gaertner WB, Bonsack ME, Delaney JP. Experimental evaluation of four biologic prostheses for ventral hernia repair. *J Gastrointest Surg.* 2007;11:1275–1285.
15. Deeken CR, Melman L, Jenkins ED, et al. Histologic and biomechanical evaluation of crosslinked and non-crosslinked biologic meshes in a porcine model of ventral incisional hernia repair. *J Am Coll Surg.* 2011;212:880–888.
16. de Castro Brás LE, Shurey S, Sibbons PD. Evaluation of crosslinked and non-crosslinked biologic prostheses for abdominal hernia repair. *Hernia* 2012;16:77–89.
17. Meintjes J, Yan S, Zhou L, et al. Synthetic, biological and composite scaffolds for abdominal wall reconstruction. *Expert Rev Med Devices* 2011;8:275–288.
18. Oelschlager BK, Pellegrini CA, Hunter JG, et al. Biologic prosthesis to prevent recurrence after laparoscopic paraesophageal hernia repair: long-term follow-up from a multicenter, prospective, randomized trial. *J Am Coll Surg.* 2011;213:461–468.
19. Franklin ME Jr, Gonzalez JJ Jr, Glass JL. Use of porcine small intestinal submucosa as a prosthetic device for laparoscopic repair of hernias in contaminated fields: 2-year follow-up. *Hernia* 2004;8:186–189.
20. Franklin M, Russek K. Use of porcine small intestine submucosa as a prosthetic material for laparoscopic hernia repair in infected and potentially contaminated fields: long-term follow-up assessment. *Surg Endosc.* 2011;25:1693–1694.
21. Ueno T, Oga A, Takahashi T, et al. Small intestinal submucosa (SIS) in the repair of a cecal wound in unprepared bowel in rats. *J Gastrointest Surg.* 2007;11:918–922.
22. Helton WS, Fisichella PM, Berger R, et al. Short-term outcomes with small intestinal submucosa for ventral abdominal hernia. *Arch Surg.* 2005;140:549–560; discussion 560–562.
23. Cobb GA, Shaffer J. Cross-linked acellular porcine dermal collagen implant in laparoscopic ventral hernia repair: case-controlled study of operative variables and early complications. *Int Surg.* 2005;90(3 Suppl):S24–S29.
24. Hsu PW, Salgado CJ, Kent K, et al. Evaluation of porcine dermal collagen (Permacol) used in abdominal wall reconstruction. *J Plast Reconstr Aesthet Surg.* 2009;62:1484–1489.
25. Adedeji OA, Bailey CA, Varma JS. Porcine dermal collagen graft in abdominal-wall reconstruction. *Br J Plast Surg.* 2002;55:85–86.

26. Liyanage SH, Purohit GS, Frye JN, et al. Anterior abdominal wall reconstruction with a Permacol implant. *J Plast Reconstr Aesthet Surg*. 2006;59:553–555.

27. Chavarriaga LF, Lin E, Losken A, et al. Management of complex abdominal wall defects using acellular porcine dermal collagen. *Am Surg*. 2010;76:96–100.

28. Sandor M, Xu H, Connor J, et al. Host response to implanted porcine-derived biologic materials in a primate model of abdominal wall repair. *Tissue Eng Part A*. 2008;14:2021–2031.

29. Connor J, McQuillan D, Sandor M, et al. Retention of structural and biochemical integrity in a biological mesh supports tissue remodeling in a primate abdominal wall model. *Regen Med*. 2009;4:185–195.

30. Itani K, Rosen M, Vargo D, et al. Prospective multicenter clinical study of single-stage repair of infected or contaminated abdominal incisional hernias using strattice™ reconstructive tissue matrix. *Abstract presented at the American College of Surgeons Meeting*, Washington, DC, October 5, 2010.

31. Rosen MJ, Reynolds HL, Champagne B, et al. A novel approach for the simultaneous repair of large midline incisional and parastomal hernias with biological mesh and retrorectus reconstruction. *Am J Surg*. 2010;199:416–420; discussion 420–421.

32. Clemens MW, Selber JC, Liu J, et al. Bovine versus porcine acellular dermal matrix for complex abdominal wall reconstruction. *Plast Reconstr Surg*. 2013;131:71–79.

33. Pomahac B, Aflaki P. Use of a non-cross-linked porcine dermal scaffold in abdominal wall reconstruction. *Am J Surg*. 2010;199:22–27.

34. Byrnes MC, Irwin E, Carlson D, et al. Repair of high-risk incisional hernias and traumatic abdominal wall defects with porcine mesh. *Am Surg*. 2011;77:144–150.

35. van Tuil C, Saxena AK, Willital GH. Experience with management of anterior abdominal wall defects using bovine pericard. *Hernia* 2006;10:41–47.

36. Limpert JN, Desai AR, Kumpf AL, et al. Repair of abdominal wall defects with bovine pericardium. *Am J Surg*. 2009;198:e60–e65.

37. Janfaza M, Martin M, Skinner R. A preliminary comparison study of two noncrosslinked biologic meshes used in complex ventral hernia repairs. *World J Surg*. 2012;36:1760–1764.

38. Patton JH Jr, Berry S, Kralovich KA. Use of human acellular dermal matrix in complex and contaminated abdominal wall reconstructions. *Am J Surg*. 2007;193:360–363; discussion 363.

39. Zhong T, Janis JE, Ahmad J, et al. Outcomes after abdominal wall reconstruction using acellular dermal matrix: a systematic review. *J Plast Reconstr Aesthet Surg*. 2011;64:1562–1571.

40. Diaz JJ Jr, Guy J, Berkes MB, et al. Acellular dermal allograft for ventral hernia repair in the compromised surgical field. *Am Surg*. 2006;72:1181–1187; discussion 1187–1188.

41. Kim H, Bruen K, Vargo D. Acellular dermal matrix in the management of high-risk abdominal wall defects. *Am J Surg*. 2006;192:705–709.

42. Jin J, Rosen MJ, Blatnik J, et al. Use of acellular dermal matrix for complicated ventral hernia repair: does technique affect outcomes? *J Am Coll Surg*. 2007;205:654–660.

43. Sacks J, Butler C. Outcomes of complex abdominal wall reconstruction with bioprosthetic mesh in cancer patients. *The Plastic Surgery Research Council 53rd Annual Meeting*, Springfield, IL, *Plast Reconstr Surg*. 2008;121(6S):39.

44. Song Z, Yang Z, Yang J, et al. Repair of abdominal wall defects in vitro and in vivo using VEGF sustained-release multi-walled carbon nanotubes (MWNT) composite scaffolds. *PLoS One* 2013;8:e64358

45. Ayele T, Zuki AB, Noorjahan BM, et al. Tissue engineering approach to repair abdominal wall defects using cell-seeded bovine tunica vaginalis in a rabbit model. *J Mater Sci Mater Med*. 2010;21:1721–1730.

46. Altman AM, Abdul Khalek FJ, Alt EU, et al. Adipose tissue-derived stem cells enhance bioprosthetic mesh repair of ventral hernias. *Plast Reconstr Surg*. 2010;126:845–854.