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REVIEW ARTICLE
ОБЗОРНАЯ СТАТЬЯ

The choice of the optimal mesh implant for hernioplasty operations depending on the properties of mesh implants

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Abstract. Silver and titanium were the first used elements in the era of hernia-strengthening biomaterials about a hundred years ago, reaching up to 150 types nowadays. The uniqueness of Deeken and Lake Mesh Classification system is its dependence of the properties of the used materials in classifying them, where three main categories of meshes was established; permanent synthetic, absorbable (of biological origin) derived; furtherly divided into composite, non-composite types, and hybrid meshes. The physical characteristics of each category are determined by the pore size, thread diameter, thickness and density. Moreover, tear resistance, suture retention, uniaxial tensile and planar biaxial tensile testing, ball burst, make it possible to refine the properties of the mesh implant. This article is devoted to understanding the types of mesh materials used for repair of the anterolateral abdominal wall hernias by highlighting the properties of their scaffold materials, coating and barriers, as well as their improvement through coating by different several materials improving their properties in order to meet the needs of sufficient and satisfactory hernia repair seeking for leadership in choosing mesh implants.

Keywords: hernia, mesh implants, Deeken and Lake Mesh Classification system

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Introduction

The manuscript presents a literature review of the structures of mesh materials according to their components and mechanical characteristics to establish their ideal application for hernia repair. sources included Research Gate, Springer, PubMed, ScienceDirect, online library, SAGES manual on hernia surgery, as well as modern research on the biomedical application of carbon nanomaterials, including graphene, in dissertation works in order to select the optimal option.

Silver and titanium were the first biomaterials to be used for reinforcement of hernia starting from the 40's of the last century, which were replaced by permanent synthetic mesh materials in the next decade reaching up to 150 types of mesh materials nowadays. The uniqueness of Deeken and Lake Mesh Classification system over other classifications; is that it clarifies the nuances in order to explain the properties of the used materials dividing them into 3 main groups; permanent synthetic, resorbable, and biological tissue-derived materials which are furtherly divided into subgroups depending on; reinforcement materials, coatings and barriers [1—4].

The physical characteristics

1. Pore sizes; microporous (< 100 μm), small pores (100—600 μm), medium pores (600—1000 μm), large pores (1000—2000 μm).

2. Fiber diameter; very large (> 200 μm), large (175—200 microm.), medium (150—175 μm.), small (125—150 μm.) and very small (<125 μm).

3. Thickness; extra thick (>1.5mm), thick (1—1.5 mm), medium (0.75—1 mm), thin (0.5—0.75mm) and very thin (< 0.5 mm).

4. Area density; heavy weight (>90g/m2), medium weight (50—90g/m2), lightweight (35—50 g/m2) and ultra-light-weight (< 35g/m2).

5. Suture retention strength; the maximum load sustained prior to failure of the suture.

6. Tear resistance testing; is the performed effort to understand the resistance of the material provides against propagation of tear once the tear has been initiated.

7. Ball burst testing; Estimating strain, stiffens and ultimate tensile strength of the tested mesh material.

8. Uniaxial tensile testing; to understand the resistance of the material provides against tension applied in two orthogonal directions simulating the conditions of the human abdomen.

9. Lap shear testing; Measuring the maximum load measured in Newton which the suture can resist achieving tissue reinforcement [2].

The first category includes permanent synthetic polymers [5, 6]:

1. Polyprolene (PP): A nonabsorbable, high tensile strength, nonpolar, electrostatically neutral, and highly hydrophobic, coated or uncoated; mono or multifilamentous. Heavy or light weight were the latter decreasing the incidence of recurrence through escaping intense inflammatory reaction and thick scar formation therefore avoids mesh contraction [7, 8].

2. Polyester (PET): Multifilamentous, polar, hydrophilic, and coated by collagen preventing adhesions, so be used intraperitoneally degradable during infections [7].

3. Extended Polytetrafluoroethylene (ePTFE): Having minimal inflammatory reaction and lower scar density; incomparison to PP and PET. However, its fixation with fine material is mandatory as it can be easily broken [9].

4. Polyvinylidene fluoride (PVDF): Is superior to PP and PET regarding its resistance to degeneration and hydrolysis, moreover, decreasing foreign body response is considered as an additional advantage as reported in some studies [10, 11].

Coatings, the permanent anti-adhesive coating group for all current designs possess Titanium. Moreover, permanent synthetic meshes are paired with resorbable barriers, biological tissue-derived barriers or resorbable coatings e.g., Omega 3[5].

Barrier materials which act as an anti-adhesive layer are classified into:

1. Permanent non-composite, include expanded PTEF (ePTFE).

2. Permanent Composite, include (ePTFE) with the exception of one silicone design (Surgimesh®).

3. Resorbable (biologically derived) include: Sodium hyaluronate/carboxymethelcellulose/ polyethylene glycol hydrogel, glycolide/caprolactone/ trimethylene carbonate, glycolide/ E caprolactone, type I collagen, polyglycolic acid/trimethylene carbonate, Polyvinylpyrrolidone/polyethylene glycol and finally the omega-3 fatty acid which represents the only available resorbable coating are represented in Table 1 [5].

Table 1

The properties of each type of the first-generation mesh implants

Product (Manufacturer)	Material	Pore Size (mm)	Absorbability	Weight (g/m2)	Filament	Tensile strength (N/cm)	Advantages	Disadvantages
Vicryl (Ethicon)	PGA	0.4	Fully (60—90 days)	56	Multifilament	78.2 ± 10.5	Eliminates infectious.	Recurrence.
Dexon (Syneture)	PGA	0.75	Fully (60—90 days)	56	Multifilament	N.A.	N.A.	Adhesions
Sefil (B-Baun)	PGA	0.75	Fully (60—90 days)	56	Multifilament	N.A.	Low risk of Secondary infection.	N.A.
Marlex (BARD)	PP	0.8	No	80—100	Multifilament	58.8	N.A.	Evokes a chronic inflammatory reaction.
3D Max (BARD	PP	0.8	No	80—100	Multifilament	124.7	Reduced pain.	Adhesions.
Polysoft (BARD)	PP	0.8	No	80—100	Multifilament	N. A.	Eliminates infection.	Adhesions
Prolene (Ethicon)	PP	0.8	No	80—100	Multifilament	156.5	Eliminates infection.	Adhesions
Surgipro (Autosuture)	PP	0.8	No	80—100	Multifilament	41.8	Flexible.	Incomplete wound Healing
Prolite (Atrium)	PP	0.8	NO	80—100	Multifilament	138	Flexible	Adhesions.
Trelex (Meadox)	PP	0.8	No	80—100	Multifilament	N.A.	Flexible	Adhesions.
Atrium (Atrium)	PP	0.8	No	80—100	Multifilament	56.2 N/cm	Tolerance to infection.	Adhesions.
Premilene (B-Braun)	PP	0.8	No	80—100	Monofilament	41.4	Flexible.	Adhesions.
Serapren (smooth)	PP	0.8	No	80—100	Multifilament	N.A.	Flexible.	Adhesions.

End of the table 1

Product (Manufacturer)	Material	Pore Size (mm)	Absorbability	Weight (g/m2)	Filament	Tensile strength (N/cm)	Advantages	Disadvantages
Parietene (Covidien)	PP	0.8	No	80—100	Multifilament	38.9 ± 5.2 .	Flexible.	Adhesions.
Prolene Light (Covidien)	PP	1—3.6	No	36—48	Monofilament	20	Flexible.	Adhesions.
Optilene (B-Baun)	PP	1—3.6	No	36—48	Monofilament	58	Eliminates pain.	Adhesions.
Mersilene (Ethicon)	POL	1—2	No	40	Multifilament	19	Eliminates infection.	Adhesions.
Goretex (Gore)	ePTFE	0.003	No	Heavy Weight	Multifilament	16	Flexible	Adhesions.

Note: PP — Polypropylene; POL — Polyester; E-PTFE — Expanded polytetrafluoroethylene; PGA — Polyglycolic acid; N.A. — Information not available [6].

Hybrid meshes are created by combination of two materials aiming to obtain advantages of both; i.e. permanent synthetic and resorbable materials; a co-polymer of glycolide and lactide or glycolide/ E caprolactone; providing mechanical support at the sites of defect, followed by gradual absorption, moreover, the combination of some types of permanent synthetic mesh materials and biologically tissue derived anti-adhesive barrier i.e. Zenapro® which is a composite of polyprolene (PP) and a non-cross-linked porcine small cell intestinal submucosa [5].

The second major category of meshes is furtherly subdivided into: non-coated without barriers or even reinforced, and coated barriers. Uncoated barriers include:

1) Poly-4-hydroxybutyrate (P4HB).
2) Ultra-pure fibroin from silk.
3) Polyglycolic acid (PGA).
4) Co-polymer of glycolide and lactide.
5) Co-polymer of polyglycolic acid and trimethylene carbonate and Co-polymer of glycolide.
6) Lactide and trimethylene carbonate.

Coated barriers by resorbable composite include: (Poly-4-hydroxybutyarate scaffold paired with a hydrogel of sodium hyaluronate/carboxymethelcellulose/ polyethyleneglycol [5]. As shown in Table 2.

Table 2

The properties of each type of the second generation meshes

Product (Manufacturer)	Material	Pore Size (mm)	Absorbable	Filament	Tensile strength (N/cm)	Weight (g/m2)	Advantages	Disadvantages
Vypro, Vypro II (Ethicon)	PP/ polyglactin 910	>3	Partially (42 days)	Multifilament	16	25 and 30	Eliminates pain.	Recurrence
Gore-Tex Dual Mesh Plus (Gore)	e-PTFE	0.003—0.022	No	Multifilament	16	Heavy Weight	Eliminates adhesions.	Infection.
Parietex (Covidien)	POL/ collagen	>3	Partially (20 days)	Multifilament	16	75	Eliminates adhesions.	Infection.
Composix EX Dulex (BARD)	PP/e-PTFE	0.8	No	Monofilament	N.A.	Light Weight	Minimizes adhesions.	Infection.
Proceed (Ethicon)	PP/ cellulose	Large	Partially (<30 days)	Monofilament	56.6	45	Eliminates recurrence	Adhesions.

End of the table 2

Product (Manufacturer)	Material	Pore Size (mm)	Absorbable	Filament	Tensile strength (N/cm)	Weight (g/m2)	Advantages	Disadvantages
DynaMesh IPOM (FEG Textiltechnik)	PP/PVDF	1—2	Partially	Monofilament	11.1	60	Biocompatibility.	Adhesions.
Sepramesh (Genzyme)	PP/sodium	1—2	Partially (<30 days)	Monofilament	N.A.	102	Reduces adhesions.	Non-flexible
Ultrapro (Ethicon)	PP/PGC-25	>3	Partially (<140 days)	Monofilament	55	28	Reduced inflammatory response.	Adhesions
Ti-Mesh (GfE)	PP/ titanium	>1	No	Monofilament	12	16	Reduced inflammatory response.	Low tensile strength
C-Qur (Atrium)	PP/omega 3	>1	Partially (120 days)	Monofilament	170 ± 20.1 N	50	N.A.	Poor anti-adhesion property.

Note: PP: Polypropylene. E-PTFE: Expanded polytetrafluoroethylene. POL: Polyester. PVDF: Polyvinylidene fluoride. PGC-25: poliglecaprone 25.N.A, Information not available in literature [6].

The third category of hernia meshes 'Biological meshes', which had been introduced to overcome the complications of synthetic meshes are furtherly divided into: Non-crosslinked: and Crosslinked as presented in Table 3 [5].

Table 3

The properties of each type of the third generation meshes.

Product (Manufacturer)	Material	Tensile Strength (MPa)	Advantages	Disadvantages
Surgisis (Cook)	Porcine (small Intestinal submucosa)	4	No refrigeration is required. Long history of safety data	Requires hydration. Susceptible to collagenases
FlexHD (JandJ)	Human (acellular dermis)	10	No refrigeration or rehydration is required	*N. A.
AlloMax (Davol)	Human (acellular dermis)	23	No refrigeration or rehydration is required. Available in large sizes	Hydration required.
CollaMend (Davol)	Porcine/Bovine (xenogenic acellular dermis)	11	No refrigeration or rehydration is required. Available in large sizes.	*N.A.
Strattice (LifeCell)	Porcine/Bovine (xenogenic acellular dermis)	18	Available in large sheets.	Limited long-term follow up.
Permacol (Covidien)	Porcine/Bovine (xenogenic acellular dermis)	39	No refrigeration or rehydration is required. Available in large sizes.	*N.A.
XenMatrix (Davol)	Porcine/Bovine (xenogenic acellular dermis)	14	Available in large sheets.	Limited long-term follow up.

Note: *N.A. Information not available in literature [6].

Mesh fixation using tacks, screws, or clips has led to numerous postoperative complications, including, vascular injury, bowel obstruction, mesh migration and neuralgia which are avoided by using Self-gripping meshes: ProGrip™ is PP self-gripping, lightweight, isoelastic; macroporous knitted

monofilament, hydrophilic mesh with absorbable micro-grips providing self-adhesive fixation during the first months after implantation with an absorption time more than 18 months. Moreover, absorption of 40 % of the mesh weight decreases postoperative foreign body sensation and chronic pain. In addition to providing a tack-free fixation during laparoscopic hernioplasty with superior fixation strength compared to Bard 3D Max™ light textile with SorbaFix™ tacks or fibrin sealant, fast recovery, easy to use, and faster than tacks and glue decreasing the cost of laparoscopic inguinal procedure are additional advantages of ProGrip™ orienting it to be a part of the green medical market products [13—16].

Adhesix™ is a self-gripping, double-sided mesh, made of two components. A knitted, monofilament polypropylene mesh (rough side) covered by a resorbable layer of polyethylene glycol (PEG) and polyvinylpyrrolidone (PVP) (smooth side), which upon moistening form a hydrogel that cross-links to the underlying tissue within 5 minutes and resolves within 7 days reducing, mesh weight to <40 g/m2 allowing easy movement and repositioning. However, poor integration, seroma formation and shrinkage are drawbacks of meshes Adhesix™ [17, 18].

Antibiotic coated mesh shows the following spectrums of bacterial strain inhibitions [19]:

1. Ampicillin coated PP meshes: *S. aureus* and *E. coli* [20].

2. Gentamicin coated polyprolene/ poliglecaprone (PP/ PGC) and PE — polyester: *S. aureus* and when coated to PVDF — polyvinylidenfluoride: *S. aureus E. coli, S. epidermidis* [21,22].

3. Cefazolin coated PGA-TMC — polyglycolic acid– trimethylene carbonate; S. aureus while when loaded on PE — polyester meshes: MRSA infection [23, 24].

4. Vancomycin coated PE — polyester meshes: *S. aureus* and MRSA infections [25].

5. Levofloxacin coated PP and PCL — polycaprolactone meshes: S. aureus, *E. coli*, while when loaded with silver on PLLA — poly-L-lactide mesh: MRSA infection [26, 27].

6. Ciprofloxacin coated PP meshes: *S. aureus*, *E. coli* infection. PCL/L-DOPA meshes coated by ofloxacin have the same zone of prevention [28, 29].

7. Rifampicin coated meshes: S. aureus and *E. coil*, while when loaded with other antibiotics like minocycline or ofloxacin: MRSA infection [1, 30].

3D Meshes

3D printing is bio-dimensional imaging of surgical meshes via layer-by-layer deposition of materials on the mesh surface which is obtained by 7 procedures: (I) fused deposition model (FDM), also known as material extrusion, (II) powder bed fusion, (III) vat photopolymerization, (IV) material jetting, (V) binder jetting, (VI) sheet lamination, and (VII) directed energy deposition, were the choice of procedure depends on many factors; type of mesh material, time of production, cost, availability of equipment, and technical expertise; i.e. FDM is used for the development of non-biological, while powder bed fusion has applications in drug delivery systems. The advantage of such layer-by-layer fabrication system is that the printed layers and compounds used can be tailored to achieve a coordinated balance between drug release and device degradation therefore enhancing tissue repair, moreover, upon loading with contrast-materials, 3D printed meshes were visible on CT [31—37].

Moreover, 4D-printing seems to resolve the limitations of 3D-printed devices to recapitulate the dynamics of living tissues by introducing “time” as a new factor, where smart thermo-polymers capable of shape changes in response to physicochemical or biochemical stimuli (e.g., temperature, pressure, presence of molecules, pH) which can be extruded via FDM approaches. These stimuli-responsive polymers allow the mesh to progressively adapt and respond to changes in the host-tissue environment, enhancing tissue ingrowth and implant compliance. Moreover, this technology can optimize drug delivery systems, enabling drug-loaded printed meshes to release their medication only and specifically when needed e.g., release of antibiotics in the presence of bacterial toxins, release of cytokines and growth factors to stimulate cell migration and vascularization [38, 39].

The choice of suitable mesh implant for hernioplasty is a multifactorial process, depending upon many factors; physical properties, advantages and disadvantages of the given implant as well as patient factors e.g., concomitant morbidities which can increases the incidence of postoperative site infection and the operative field anatomical site, virginity and appropriate site of mesh implantation.

Among the three successive generations of mesh implants; the first generation: permeant non-absorbable mesh implants have the benefit of being long lasting with good tensile strength, beside hybrid mesh subtype possesses having the advantages of both mixed types. The second generation: coated-mesh implants, have the advantage of being light-wight and partially absorbable. The third generation: biological mesh implants are being biologically inert and completely absorbed by the patient tissues. Furthermore, new upgrades have involved theses mentioned generation achieving the self-gripping mesh implants, carbon nano-coated mesh implants as we all 3D and even 4D mesh implants aiming at achieving the concept of the most optimal mesh implants with maximum benefits and minimum drawbacks (green meshes).

Conclusion

The concept of optimal or best mesh is unfit for practical application, as the selection of appropriate mesh for every type of hernia repair operation is guided by the properties of the mesh to be chosen in order to fulfill the requirements of the favorable repair.

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Выбор оптимального сетчатого имплантата для операций герниопластики в зависимости от свойств сетчатых имплантатов

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Аннотация. Серебро и титан были первыми используемыми элементами в эру биоматериалов, укрепляющих грыжу, около ста лет назад, и в настоящее время их количество достигает 150 видов. Уникальность системы классификации сетчатых имплантатов Дикен и Лейк заключается в ее зависимости от свойств используемых материалов при их классификации, где были установлены три основные категории сетчатых имплантатов: постоянные синтетические, рассасывающиеся (биологического происхождения), далее разделенные на композитные и некомпозитные типы, а также гибридные сетчатые имплантаты. Физические характеристики каждой категории определяются размером пор, диаметром нити, толщиной и плотностью. Кроме того, прочность на разрыв, сохранение швов, испытание на одноосное растяжение и плоскостное двухосное растяжение, разрыв шарика позволяют уточнить свойства сетчатого имплантата. Статья посвящена изучению типов сетчатых материалов, используемых для лечения грыж переднебоковой стенки живота, с описанием свойств их каркасных материалов, покрытия и барьеров, а также их усовершенствованию.

Ключевые слова: грыжа, сетчатые имплантаты, система классификации сетчатых имплантатов Дикен и Лейк.

Информация о финансировании. Авторы заявляют об отсутствии финансирования.

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