DEVELOPMENT OF MESH IMPLANTS MATERIALS THROGH HISTORY REGARDING THEIR CHARACTERISTICS. REVIEW STUDY

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ABSTRACT Hernaition process is augmented by well-known risk factors; evolutionary weak points of the anterolateral abdominal wall e.g., linea alba and the groin; iatrogenic weakness of the anterolateral abdominal wall e.g., surgical interventions in the anamnesis, besides elevated intra-abdominal pressure. Others, that could alter the herniation patterns are; morbid obesity, lack of mobility, decreased birth rate and other social factors. The aim of classification of hernia is to establish a standardized protocol identifying type, determining examination tactics, as well as selecting the most optimal surgical technique. The same idea is applied to the classification of surgical meshes materials, physical properties, pons and cons, aiming at selecting the most appropriate mesh for every given hernioplasty procedure. An everyday rapidly growing modifications are applied upon the structure, coatings even methods of coating the surgical mesh implants targeting more adaptation in between the implanted mesh and its surrounding tissue, thus eliminating the incidence of the expected drawbacks therefore promoting the hernioplasty procedure. For this target, we are highlighting the properties of mesh implants depending upon their structural materials in this study.

KEYWORDS Hernia, surgical mesh, hernioplasty, surgical mesh classification

Introduction

The paper provides an overview of the development of mesh implant materials for hernia repair, covering three main generations of meshes: permanent non-absorbable meshes, coated and partially absorbable meshes, and biological meshes. The paper also discusses newer innovations like self-gripping, 3D printed meshes, and 4D printed meshes that can adapt to the host environment.

The study objectives were to search for information on the fundamentals of using mesh materials, their components and mechanical characteristics to establish their optimal use for hernioplasty (hernia repair surgery) and to understand the concept of "Green Nano mesh".

The independent variables in this paper appear to be the physical characteristics of the mesh implants, including pore size, fibre diameter, thickness, and weight. The dependent variables in this study appear to be the physical characteristics of the mesh

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implants, including pore size, fibre diameter, thickness, weight, maximum load sustained, resistance to tear propagation, strain, stiffness, ultimate tensile strength, resistance to tension, and maximum suture load.

The measured variables in this study appear to be the pore size, fibre diameter, thickness, weight, maximum load sustained prior to failure, resistance to tear propagation, strain, stiffness, ultimate tensile strength, resistance to tension in two directions, and maximum load the suture can resist. The experimental techniques in this paper are Fused deposition modelling (FDM) - Powder bed fusion - Vat photopolymerization - Material jetting - Binder jetting - Sheet lamination - Directed energy deposition - and 4D printing using smart thermo-polymers.

The specific algorithms introduced, studied, or used in the study include 3D printing techniques such as fused deposition modelling (FDM), powder bed fusion, vat photopolymerization, material jetting, binder jetting, sheet lamination, and directed energy deposition, as well as 4D printing using smart thermopolymers. The research question: What are mesh materials' key characteristics and developments for hernia repair?

Silver and titanium were the first biomaterials to be used for reinforcement of hernia starting in 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 & 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 further divided into subgroups depending on; reinforcement materials, coatings and barriers. [1-4].

The physical characteristics on which Deeken & Lake system relies are:

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), light-weight (35-50 g/m2) and ultra-light-weight (<35g/m2).

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

6. Tear resistance testing is the effort to understand the material's resistance against the propagation of the tear once the tear has been initiated.

7. Ball burst testing: Estimating the tested mesh material's strain, stiffens, and ultimate tensile strength.

8. Uniaxial tensile testing: to understand the material's resistance against tension applied in two orthogonal directions, simulating the conditions of the human abdomen.

9. Lap shear testing: Measure the maximum load measured in Newton, which the suture can resist, to achieve tissue reinforcement [2].

The first category includes permanent synthetic polymers [5]:

1. Polypropylene (PP): A nonabsorbable, high tensile strength, nonpolar, electrostatically neutral, and highly hydrophobic, coated or uncoated; mono or multifilaments. Heavy or lightweight, the latter decreased the incidence of recurrence by escaping intense inflammatory reaction and thick scar formation, therefore avoiding mesh contraction [6,7].

2. Polyester (PET): Multifilamentous, polar, hydrophilic, and coated by collagen-preventing adhesions, it can be used intraperitoneally degradable during infections [6].

3. Extended Polytetrafluoroethylene (ePTFE): It has a minimal inflammatory reaction and lower scar density than PP and PET. However, its fixation with fine material is mandatory as it can be easily broken [8].

4. Polyvinylidene fluoride (PVDF) Is superior to PP and PET due to its resistance to degeneration and hydrolysis; moreover, decreasing foreign body response is considered an additional advantage, as reported in some studies [9, 10].

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, including expanded PTEF (ePTFE).

2. Permanent Composite, including (ePTFE) except for 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 [5].

The properties of each first-generation mesh implant in the markets are illustrated in Table 1 [11].

Hybrid meshes are created by the 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 meshes category is further 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.

Table 1 The properties of each type of the first-generation mesh implants in the markets [11].

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.
Premilen® (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.
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.

PP: Polypropylene. POL: Polyester. E-PTFE: Expanded polytetrafluoroethylene. PGA. Polyglycolic acid. N.A. Information not available.

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: (A poly-4-hydroxybutyrate scaffold paired with a hydrogel of sodium hyaluronate/carboxymethylcellulose/polyethyleneglycol [5].

The properties of each type of second-generation meshes in the markets are illustrated in Table 2 [11].

The third category of hernia meshes, 'Biological meshes', which had been introduced to overcome synthetic meshes' complications, are further divided into Non-crosslinked and Crosslinked [5]. The properties of each type of third-generation meshes in the markets are illustrated in table 3 [11].

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 [12-15]. 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 forms 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™ [16, 17]

Antibiotic-coated mesh shows the following spectrums of bacterial strain inhibitions [18].

Table 2 The properties of each type of the second generation meshes in the markets [11].

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 & 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	Eliminate recurrence	Adhesions.
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.

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

1. Ampicillin-coated PP meshes: S. aureus and E. coli [19].

2. Gentamicin coated polyprolene/ poliglecaprone (PP/ PGC) and PE—polyester: S. aureus and when coated to PVDF—polyvinylidene fluoride: S. aureus E. coli, S. epidermidis [20,21].

3. Cefazolin coated PGA-TMC—polyglycolic acid– trimethylene carbonate; S. aureus while when loaded on PE—polyester meshes: MRSA infection [22,23].

4. Vancomycin-coated PE—polyester meshes: S. aureus and MRSA infections [24].

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 [27, 28].

7. Rifampicin-coated meshes: S. aureus and E. coil, while loaded with other antibiotics like minocycline or ofloxacin: MRSA infection [1,29].

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 a 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 [30-36].

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 thermopolymers 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 envi-

Table 3 The properties of each type of the third generation meshes in the markets [11].

Product (Manufacturer)	Material	Tensile Strength (MPa)	Advantages	Disadvantages
Surgisis® (Cook)	Porcine (small intestine submucosa)	4	No refrigeration is required. Long history of safety data	Requires hydration. Susceptible to collagenases.
FlexHD® (J&J)	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.

*N.A. Information not available in literature.

ronment, 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., the release of antibiotics in the presence of bacterial toxins, the release of cytokines and growth factors to stimulate cell migration and vascularization [37,38].

Future research should explore the potential of 4D printing to develop mesh implants that can adapt and respond to changes in the host tissue environment, potentially enhancing tissue integration and enabling targeted drug delivery [39]. Furthermore, the process of promoting surgical mesh implants had extended to include methods of mesh implant fixation. This development was achieved aiming at overcoming the side effects of classical suture fixation e.g., prolonged time of operation, postoperative neuralgia and postoperative seroma. For this target, self-gripping mesh as well as mesh fixation by tacks in both laparoscopic as well as open anterior hernioplasty achieved the targets of eliminating operative-time, postoperative complications besides decreasing the incidence of chronic postoperative complications and the rates of hernial recurrences [40,41].

Results

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 increase the incidence of postoperative site infection and the operative field anatomical site, virginity and appropriate site of mesh implantation.

Discussion

The paper provides an overview of the development of mesh implant materials for hernioplasty, covering three generations of mesh implants and their characteristics, as well as newer developments in mesh implants aimed at achieving optimal mesh implants with maximum benefits and minimum drawbacks ("green meshes").

Conclusion

The choice of mesh implant for hernioplasty is a multifactorial process that depends on the mesh's physical properties, advantages, and disadvantages, as well as patient factors and the specific requirements of the hernia repair operation. There is no single "optimal" or "best" mesh, as the specific requirements of the hernia repair operation should guide the selection.

Conflict of Interest:

Mekhaeel Mekhaeel, Sameh Salem and Andrey Protasov declare no conflicts of interest.

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Ethical Approval

This article is based on previously conducted studies and does not contain any new studies with human participants or animals performed by any of the authors.

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