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Mosquito Net Mesh for Abdominal Wall Hernioplasty: A Comparison of Material Characteristics with Commercial Prosthetics

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Abstract
Background The use of sterilized mosquito net as a cheaper alternative to commercial mesh used in hernia repair has previously been published. However, as no standards with regard to the material have been documented, we aimed to define the characteristics of a commonly available and low-cost mosquito net, which has already been shown to be clinically efficacious in groin hernia repair. We compared its characteristics to other commercially available meshes, in keeping with the well-established FDA and MHRA regulatory processes.
Methods The macromolecular structure of the mosquito net was determined by vibrational spectroscopy. The ultrastructure of the meshes was examined with scanning electron microscopy, and uniaxial and burst tensile strength testing was performed. The following parameters were assessed: polymer type, filament characteristics, pore size, weight, linear density, elasticity, and tensile strength.
Results The mosquito net was a polyethylene homopolymer, knitted from monofilament fibers with a mean filament diameter of 109.7 μm and a mean mesh thickness of 480 μm. The mean pore maximum diameter was 1.9 mm, with 91.2 % porosity, 53.7 g/m^2 mean mesh weight, and a linear mass density of 152 denier. This was comparable to the "large pore" (class I) commercial meshes. The bursting force for polyethylene mosquito net was greater than for UltraPro and Vypro (43.0 vs. 35.5 and 27.2 N/cm, respectively), and the mosquito net exhibited less anisotropy compared to the commercial meshes.
Conclusions The material and mechanical properties of the polyethylene mosquito net are substantially equivalent to those of commonly used lightweight commercial meshes.

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Introduction

The implications of neglected inguinal hernias in resource-limited settings are well documented [1–7]. In rural areas of underdeveloped countries, where poverty is endemic and modern healthcare is a luxury, there is an unspoken global acceptance of allowing patients to live with chronic disabilities such as hernias [8]. In these settings, solutions that entertain cheaper alternative and innovative technologies are clearly worth exploring. One example is the use of sterilized mosquito net as an alternative to the more expensive commercial mesh used in hernia repair. The use of prosthetic mesh to reinforce the abdominal wall in inguinal hernia repair is now accepted as the gold standard and has led to recurrence rates below 5 % [9–11]. In most low income, resource-poor developing countries, however, a traditional sutured repair, with significantly inferior results, is still commonplace, as commercial mesh is either unavailable or unaffordable [12].

Synthetic hernia meshes date back to the early 1900s, but their use was only popularized in the 1950s [13]. The hernia healthcare industry has since developed over 200 types of mesh, with costs ranging from US$40 to US$6,000 per mesh [3]. The most commonly used macroporous polymers are polypropylene and polyester, which differ in their ultrastructure, filament type/construction, pore size, weight/density, tensile strength, and elasticity [14]. These commercial hernia meshes are categorized as a class II medical device and are required to undergo the US Food and Drug Administration (FDA) premarket notification (510(k)) process in the United States or the Medicines and Healthcare products Regulatory Agency (MHRA) or other competent authority approval in the UK and Europe prior to release onto the market [15].

The term *mosquito net* dates from the mid-eighteenth century; however, the use of such devices has been dated to prehistoric times [16]. Mosquito nets vary in their construction, but the most common polymer types are cotton, polyethylene, nylon, and polyester [17]. To stop mosquitoes the pore size must be smaller than 1.2 mm; however, many nets use a pore size of 0.6 mm in order to stop other biting insects [17]. In recent years, a number of studies in developing countries have examined the use of locally available mosquito net, of various polymers, for hernia repair [4–7, 18]. However, because no standards with regard to the material have been documented, we aimed to define the characteristics of a commonly available and low-cost (polyethylene) mosquito net, which has already been shown to be clinically efficacious in groin hernia repair [19]. We compared its characteristics to other commercially available meshes, in keeping with the well-established FDA and MHRA regulatory processes.

Materials and methods

Materials—prosthetic meshes

The test article was 121 °C steam sterilized 11 × 6 cm (polyethylene) mosquito net produced by Amsa Plastics, Karur, India, and used by the nonprofit charitable organization "Operation Hernia" for hernia repair in developing countries. The other articles in the comparison described five commercially available meshes, all FDA and MHRA approved, for use in abdominal wall hernia repair. These included two uncoated polypropylene meshes, one uncoated polyester mesh, and two partially absorbable meshes (polypropylene/polyglactin 910 and polypropylene/polyglecaprone). These are the commercial products Prolene (Ethicon Inc., Johnson &Johnson, New Brunswick, NJ), Bard Mesh (Davol Inc., SUB C.R. Bard Inc., Warwick, RI), Parietex (Sofradim, Trevoux, France), Vypro (Ethicon Inc., Johnson and Johnson, New Jersey, USA), and UltraPro (Ethicon Inc., Johnson & Johnson). Data for the polymer type and tensile strength for these meshes were obtained directly from the manufacturers.

Polymer type

The macromolecular structure of the mosquito net was determined by vibrational spectroscopy. The equipment used was the Fourier Transform Infrared (FTIR) spectrometer fitted with a diamond Attenuated Total Reflection (ATR) compression cell, Alpha FT-IR, Bruker Optics, Ettingen, Germany; and the software OPUS v 6.5 was used for spectral data analysis. The analysis of transmission FTIR results was performed under the following conditions: resolution of 4 cm^{-1} at the band of 4,000–375 cm^{-1}. The spectrum was background corrected, and absorption FTIR analysis was performed using the band of 1,500–700 cm^{-1}.

Ultrastructure

Meshes were fixed with 3 ml of 2.5 % glutaraldehyde for 24 h; excess glutaraldehyde was removed by three gentle rinses with distilled water performed under a laminar flow hood. Specimens were serially dehydrated in ethanol (10, 25, 50, 75, 95, 100, 100 %) air-dried, mounted on metal stubs, and sputter coated with gold. The ultrastructure of the mesh (filament type) was analyzed in a JEOL JSM-7001F scanning electron microscope at 25× and 500× magnification. Digital photographs taken with the integrated image capture on the scanning electron microscope were used for comparison of the meshes. Image J software version 1.44 (Wayne Rasband, National Institutes of Health, USA) was used to perform a morphometric analysis to measure the diameter of the mesh filaments (μm) and the thickness (diameter) of the mesh according to DIN EN ISO 5084 standards. Ten measurements were taken for each mesh, and the results were reported as mean ± standard error of the mean (SEM).

Weight and density

The dry weight and relative density were measured with an electronic scale (Salter-Brecknell-ESA-300; Avery Weigh-Tronix, Fairmont, MN) and a 5 ml pyncnometer (Equilabor, São Paulo, Brazil). The measurements were taken using distilled water at room temperature. Mesh weight per area ratio (g/m^2), as well as the denier linear mass density (mass in g/9,000 m) were determined.

Pore size

The pore size was measured in the JEOL JSM-7001F scanning electron microscope at 25× magnification, with the Image J software version 1.44 particle analyzer tool. Specimens were prepared for scanning electron microscopy as previously described. Fifty pores were analyzed at random, and measurements were taken of the area (μm^2) and

Feret (the longest distance between any two points along the selection boundary, also known as maximum caliper). The percentage porosity was calculated with the following equation:

$$\%\ \text{Porosity} = \text{pore space}/\text{total volume} \times 100.$$

Results were expressed as mean ± SEM.

Tensile strength and elasticity

Tensile strength and elasticity measurements were performed by Heathcoat Fabrics Ltd., Tiverton, UK, in accordance with the CEN/CENELEC European standards. Dry specimens were tested at room temperature with no preconditioning. Uniaxial tensile strength testing was performed by the BS EN ISO 1394-1 strip test method in the vertical (warp) direction and by the universal tensile testing system (Instron-4301) in the horizontal (weft) direction. Pneumatic grips set to 60 psi were use to clamp each specimen, leaving a 2.5 cm gauge length. Each specimen was tested in tension at a rate of 25 mm/min until the mesh ruptured. This was repeated in both the warp and weft directions. The tensile strength (N/cm) was calculated from the maximum load sustained by the mesh per cm of mesh material. The subsequent force required to tear the mesh (N) was measured by the DIN 53859-2 leg tear method with the universal tensile testing system (Instron-5655). For this type of testing, mesh specimens measuring 2 × 7 cm were prepared, and a 2.5 cm slit was cut from the edge of the specimen toward the center of the mesh to form 2 tabs or "pant legs." The left tab was clamped in the upper grip of the Instron machine with a pneumatic grip of 60 psi, and the right tab was clamped in an identical fashion in the lower grip. This arrangement yielded a 2.5 cm gauge length. The specimen was orientated in the weft direction and then was repeated in the warp direction. The test was conducted in tension at a rate of 300 mm/min until the specimen tore in half. The tear strength was recorded as the maximum load sustained by the mesh (N) and is reported as mean ± SEM. For measurement of the burst pressure, the test specimen was clamped over an expansive diaphragm with a circular clamping ring in accordance with the BS EN ISO 13938-2 pneumatic bursting method. Mesh orientation was not considered because of the biaxial nature of the test. The maximum bursting force (N) and the percentage extension of the mesh at 16 N were recorded. The percentage extension corresponds to the increased mesh area compared with the initial area of the mesh before deformation.

Data analysis

Data are presented as means ± SEM to one decimal place and have undergone descriptive analysis. Tensile strength data were evaluated with an unpaired, two-tailed *t*-test; a *P* value of <0.05 considered to be significant.

Results

The overall structure of the meshes, including the polymer type, filament type, filament diameter, thickness, weight, fineness of the yarn, and pore size measurement, as well as the biomechanical properties of each mesh, are shown in Table 1.

Polymer type

Fourier transform infrared analysis of the mosquito net exhibited bands at 670 cm^{-1} alkyl C–H out of plane skeletal vibrations, 1,500 cm^{-1} alkyl C–H deformation, and 2,900 cm^{-1} alkyl CH_2 stretch (with a strongly absorbing double band). From these it is possible to infer that the polymer is a polyethylene homopolymer (Fig. 1). The polymer types of the commercial meshes are shown in Table 1.

Ultrastructure

Mosquito net, Prolene, and Bard Mesh are knitted from monofilament fibers, whereas Parietex and Vypro are multifilament meshes (Fig. 2). The mean thickness of the mosquito net was 480 ± 7 μm, which is comparable to the commercial meshes analyzed, which ranged from 460 ± 8 to 535 ± 7 μm.

Weight

The mosquito net was similar in weight to the lightweight commercial meshes Vypro and UltraPro (53.7 vs. 54.0 and 52.5 g/m^2, respectively; Table 1). These were considerably lighter than the other commercial meshes analyzed (Fig. 3). It should be noted that Vypro and UltraPro are partially absorbable and contain polyglactin and polyglecaprone, respectively. These components dissolve over time, leaving only the polypropylene material behind as a permanent repair. The weight of the polypropylene components was 26.0 g/m^2 for Vypro and 28.0 g/m^2 for UltraPro, and thus the post-absorption weight of both these meshes is lighter than mosquito net mesh. The fineness of the yarn of mosquito net was 152 denier, the same as UltraPro and slightly greater than Vypro (140 denier). All the other meshes had a higher denier than the mosquito net (Table 1).

Pore size

The mean pore size of the mosquito net (1.9 ± 0.1 mm) was larger than that of Prolene, Parietex, and Bard Mesh

Table 1 Results of physiomechanical testing (data are mean ± SEM)

	Mosquito net	Prolene	Parietex	Bard Mesh	Vypro	UltraPro
Manufacturer	Amsa Plastics	Ethicon	Covidien	Bard	Ethicon	Ethicon
Mesh size (cm)	6 × 11	6 × 11	6 × 11	7.5 × 15	10 × 15	6 × 11
Ultrastructure						
Polymer[a]	Polyethylene	Polypropylene	Polyethylene phthalate	Polypropylene	Polypropylene + polyglactin 910	Polypropylene + Poliglecaprone
Filament	monofilament	monofilament	multifilament	monofilament	multifilament	monofilament
Filament diameter (μm)	109.7 ± 0.6	130.4 ± 2.4	338.8 ± 3.7	185.7 ± 1.7	90.0 ± 0.6	102.5 ± 0.9
Thickness (μm)	480.0 ± 4.0	535.0 ± 7.0	520.0 ± 5.0	530.0 ± 7.0	460.0 ± 8.0	500.0 ± 6.0
Weight and density						
Weight (g/m^2)	53.7	108.1	129.6	95.1	54.0[b] (26.0)	52.5[b] (28.0)
Fineness of yarn (denier)	152	185	882	170	140	152
Pore size						
Mean maximum feret (mm)	1.9 ± 0.1	1.6 ± 0.1	1.7 ± 0.1	0.8 ± 0.1	4.9 ± 0.1	3.8 ± 0.1
Mean pore area (μm^2)	1,894.4 ± 189.2	390.0 ± 20.6	1,750.2 ± 30.1	440 .4 ± 20.2	4,370.6 ± 80.1	4,100.2 ± 60.8
% Porosity	91.2	84.7	79.0	85.4	91.1	96.7
Tensile strength[a]						
Maximum tensile strength (N/cm)						
Vertical (warp)	42.7	119.4	78.2	86.4	77.4	69
Horizontal (weft)	31.5	153.4	127.2	113.4	12.6	18.4
Subsequent tearing force (N)						
Vertical (warp)	9.4	44.1	27.8	40.3	11.6	12.2
Horizontal (weft)	7.2	0.1	33.6	6.6	10.6	8.8
Test pressing through the stamp						
Maximum bursting force (N/cm)	43.0 ± 3.2	156.6 ± 9.2	112.9 ± 3.0	157.7 ± 8.0	27.2 ± 3.7	35.5 ± 1.7
Deformation at 16 N/cm (%)	26.0 ± 4.5	6.3 ± 0.1	3.5 ± 0.1	10.8 ± 0.2	22.0 ± 0.7	18.2 ± 7.1

[a] Data obtained from manufacturers

[b] These are partially absorbable meshes the remaining weight of polypropylene after absorption is shown in parentheses

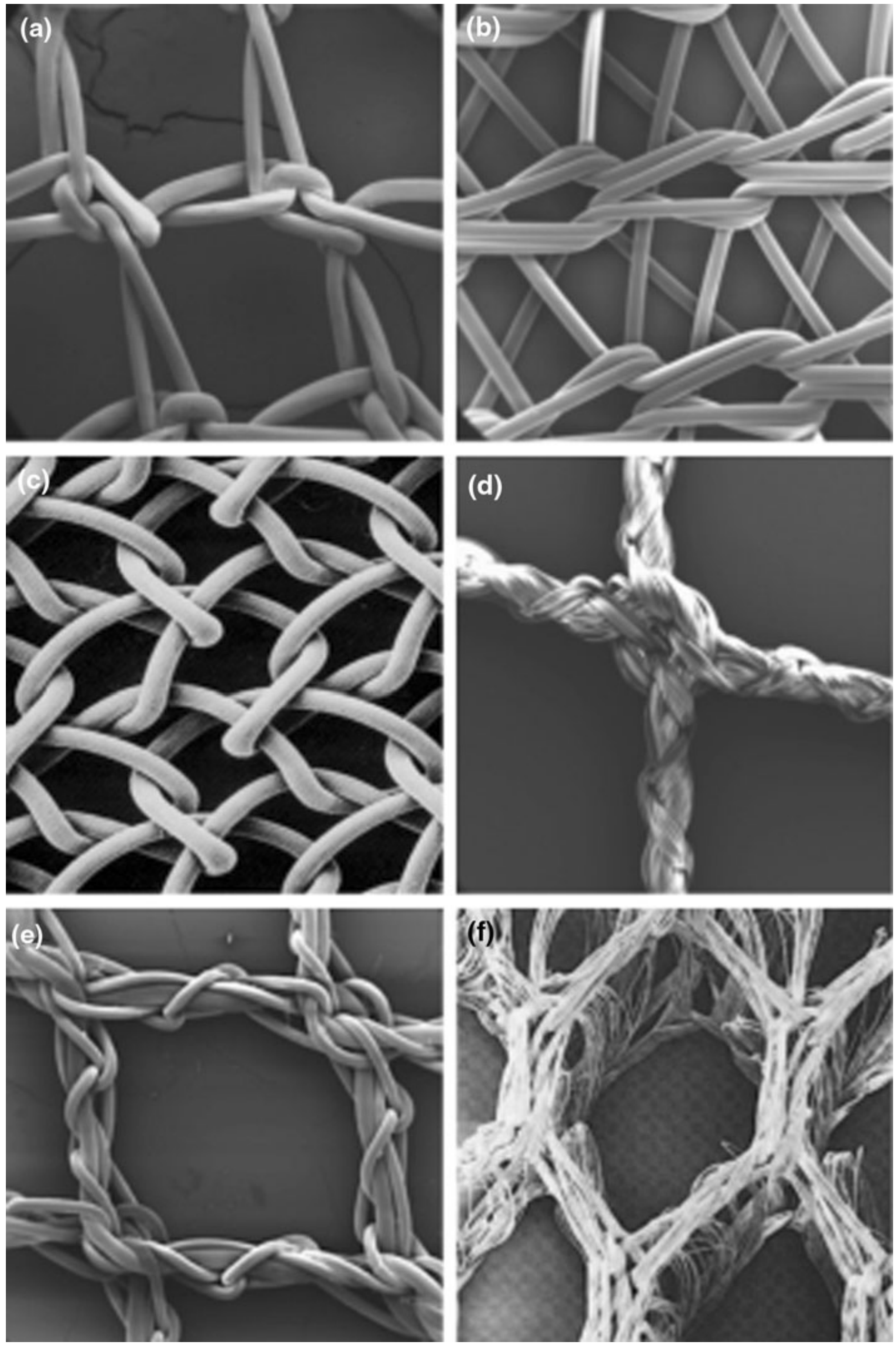

Fig. 1 Low power electron microscopy demonstrating the ultrastructure of polyethylene mosquito net compared to the commercial meshes analysed (JEOL scanning electron microscope ×25 original magnification) **a** polyethylene mosquito net, **b** Prolene®, **c** Bard® mesh, **d** Vypro®, **e** UltraPro®, **f** Parietex™

(1.6 ± 0.1, 1.7 ± 0.1, and 0.8 ± 0.1 mm, respectively), but smaller than Vypro (4.9 ± 0.1 mm) and UltraPro (3.8 ± 0.1 mm). This is represented on the scatter plot in Fig. 3. The mosquito net had similar percentage porosity to Vypro (91.2 vs. 91.1 %). UltraPro had the greatest percentage porosity (96.7 %), and the heavier meshes had lower percentage porosities, ranging from 79 to 85.4 %.

Tensile strength

All the meshes except Vypro (in the weft direction) withstood tensile stresses greater than 16 N. The meshes evaluated in this study displayed significantly different maximum tensile strengths depending on the orientation of the mesh during the test (i.e., in parallel "warp" or perpendicular "weft" to the longest dimension of the mesh).

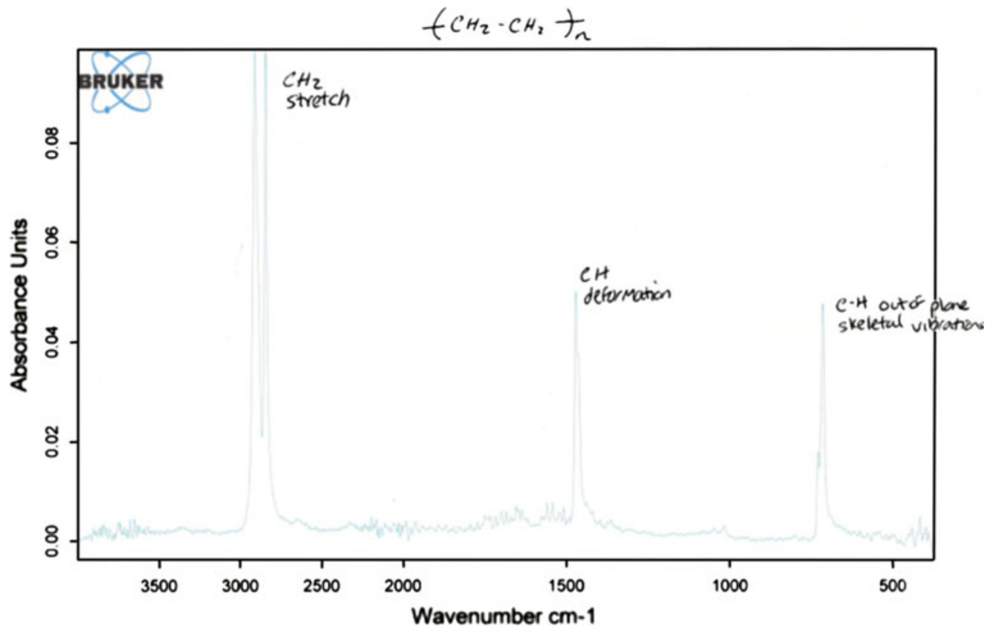

Fig. 2 FTIR spectrum for mosquito net

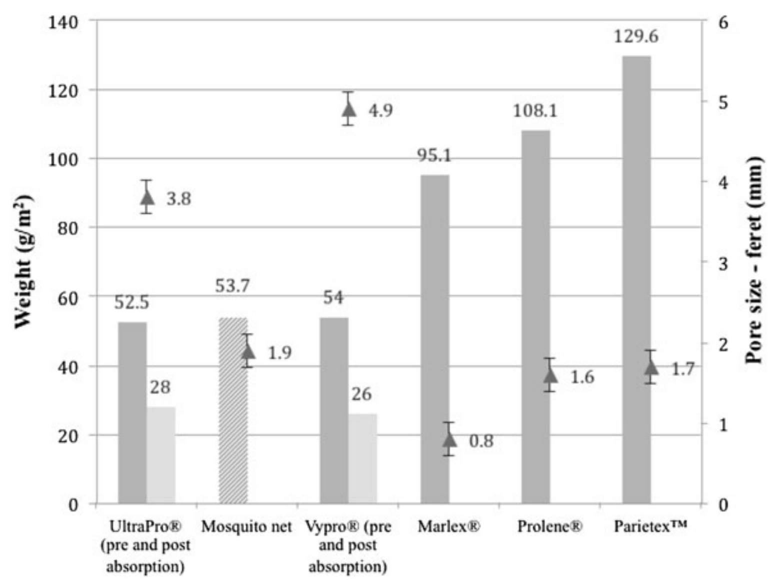

Fig. 3 Weight and pore size of mosquito net compared to commercial hernia meshes (weight displayed as *columns* and pre and post absorption weights shown where applicable. Mean pore sizes displayed as a *scatter plot* with the SEM shown)

Interestingly, the lighter weight meshes (mosquito net, Vypro, and UltraPro) displayed significantly greater maximum tensile strength in the weft direction than in the warp direction ($P < 0.01$). Conversely, the heavier weight meshes (Prolene, Bard Mesh, Parietex) showed a significantly greater tensile strength in the warp direction than in the weft direction ($P < 0.05$). Subsequent tearing of the mesh required significantly lower forces for all of the meshes ($P < 0.01$). Prolene and Bard Mesh were significantly stronger in the weft direction than in the warp direction ($P < 0.01$), with Prolene only requiring a force of 0.1 N to result in a subsequent tear. The direction of subsequent tearing force was not significant for the other meshes.

All the meshes evaluated in this study displayed tensile strengths at burst greater than 16 N/cm. The tensile strength "at burst" for mosquito net was 43.3 N/cm, which was higher than Vypro and UltraPro (Fig. 4). The other meshes had tensile strengths at burst greater than 100 N/cm. At a stress of 16 N/cm, the mosquito net displayed 26.0 ± 4.5 % deformation, which was significantly greater than the heavier weight meshes (Prolene, Bard Mesh, Parietex), but not significantly different from the lightweight meshes (Vypro and UltraPro). There was no significant difference in the

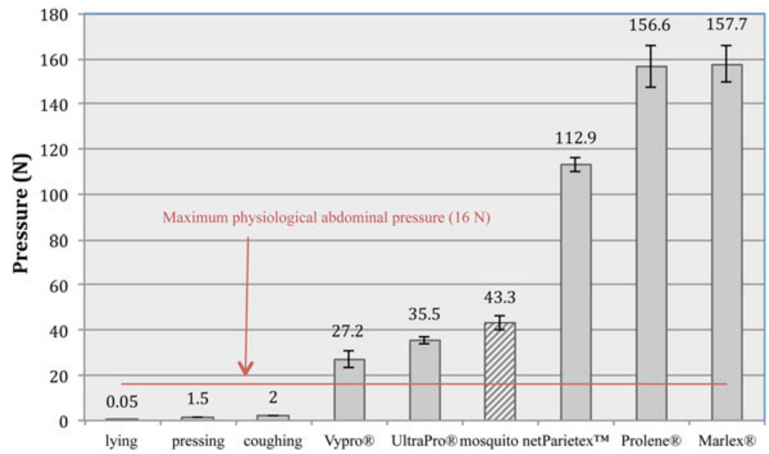

Fig. 4 Comparison of abdominal pressure with burst strength of mosquito net and commercial hernia meshes

maximum tensile strengths, subsequent tearing forces, maximum bursting force, or percentage deformation at 16 N between mosquito net and the lightweight (Vypro and UltraPro) commercial meshes.

Discussion

In general terms, the biocompatibility of synthetic (alloplastic) meshes is determined by the extent of the patient's response to the implanted foreign body, as well as by the material characteristics of the mesh [20]. In the present study we compared the material characteristics of a widely available, low-cost mosquito net with a selection of commercially available macroporous meshes commonly used for hernia repair, in an attempt to confirm or refute equivalence.

In developed countries, the most commonly used polymers for the construction of surgical meshes are polypropylene, polyethylene terephthalate (polyester), and submicronic polytetrafluoroethylene (ePTFE). Unlike these meshes, the mosquito net analyzed was constructed from a monofilament polyethylene homopolymer. The first generation of Marlex mesh ("Marlex-50"), which was pioneered by Usher in 1958, was made of polyethylene. The drawback of polyethylene is that its melting point is 122 °C, which is unsuitable in high-pressure steam sterilizers, where the temperature rises to at least 134 °C. However, as the vast majority of rural hospitals in developing countries use bench top vertical autoclaves, where the temperature reaches only 121 °C, the polyethylene mosquito mesh can be sterilized without damage. While this may cause anxiety and scepticism, steam sterilization at 121 °C for at least 15 min is a well-established and accepted method for sterilizing medical devices and is recommended by the Medical Device Agency in the United Kingdom [21]. Another option for the sterilization of polyethylene-based prosthesis is ethylene oxide (EO) sterilization. However, this is a very much more expensive option that is not widely available is and impractical in poorly resourced rural settings [22]. Interestingly, however, a recently published small randomized trial comparing EO sterilized polyethylene mesh with polypropylene mesh reported no significant differences in infection or recurrence at 2-year follow-up [6].

The present study has demonstrated that the polyethylene mosquito net has a mean pore maximum diameter of 1.9 mm, 91.2 % porosity and 53.7 g/m^2 weight, comparable to the "large pore" (class I) commercial meshes. The flexural rigidity of a mesh is related to the diameter to the fourth power, and therefore small changes in the filament diameter have a big impact on flexibility of the mesh. In a human cadaver model, Junge et al. [23] determined that the normal physiological stretch on the abdominal wall at 16 N/cm is 10–30 % (variations were due to the direction of strain and the gender of the patient). Our polyethylene mosquito net has a mean filament diameter of 109.7 μm and a mean thickness of 480.0 μm, and thus is considerably smaller that the heavyweight meshes (Prolene, Bard Mesh, Parietex) but comparable to the lightweight meshes (Vypro, UltraPro) assessed in this study. The corresponding flexibility (as defined by the percent deformation at 16 N/cm) was 26 %, which was much greater than the heavyweight meshes (range: 6–11 %), and which is well within the normal physiological values for the abdominal wall, as illustrated in Fig. 4. Irrespective of structural differences, mesh materials should be able to withstand the tensile stresses placed on the abdominal wall, which are in the order of 16 N/cm for hernia repair and 32 N/cm for complete abdominal wall reconstruction (although this may be as high as 42.5 N/cm in obese patients) [24, 25]. The tensile strength of all the meshes evaluated in this study, including the polyethylene mosquito net, exceed the requirements for hernia repair. The bursting force for polyethylene mosquito net was greater than that for UltraPro and Vypro (43.0 vs. 35.5 and 27.2 N/cm, respectively), but these meshes should probably not be used for abdominal wall reconstruction purposes, where higher tensile strengths are often required.

All of the meshes evaluated in the present study showed signs of anisotropy (i.e., different strengths depending on mesh orientation). The degree of anisotropy was lower for polyethylene mosquito net than for the other meshes, which suggests that its strength is retained in all directions. However, the anisotropic properties of the meshes highlight the importance of orientating the mesh with its strongest direction parallel to the greatest stress on the abdominal wall (i.e., transversely); for polyethylene mosquito net, this is the vertical (warp) direction.

Despite several studies demonstrating that mosquito net can be implanted with low complication rates, using the global term *mosquito net* to describe all of these meshes has potential problems. Mosquito net meshes with unknown polymers, coatings, and biomechanical properties may lead to intense inflammatory responses, and even mesh extrusion. The normal regulatory approval of commercial hernia meshes starts with experimental and animal studies, followed by clinical trials in order to demonstrate substantial equivalence to an already established device. The evaluation of the use of mosquito net mesh for this purpose has undergone this process in reverse. This, in part, reflects the desperate need for affordable novel technologies in developing countries but also the complexity and variation of regulatory procedures worldwide. Several clinical studies have demonstrated the effective use of mosquito net for hernioplasty; however, there has been significant heterogeneity in the type of mosquito nets used, which include nylon, a polyethylene-polypropylene mix, and polyester [4, 7, 18]. The compiled data, including five randomized clinical studies, includes 7,032 hernia operations [4, 5, 7, 18, 19, 26, 27]. This included 6,341 inguinal hernias with a 0.7 % recurrence rate and 0.1 % mesh rejection rate, and 691 incisional and other abdominal wall hernias with a 4.7 % recurrence rate and 0.65 % mesh rejection rate. Despite these promising results, the heterogeneity of the mosquito net meshes, and in some cases the ad hoc follow-up regimes, mean that the results should be interpreted with caution. Nevertheless the results are superior to those of sutured repairs.

In summary we have demonstrated that the material and mechanical properties of the polyethylene mosquito net are equivalent to those of commonly used lightweight commercial meshes. Polyethylene mosquito net is extremely cheap and widely available. The cost advantage of polyethylene mosquito net compared to commercially produced mesh is substantial. The pre-packaged cost of the mosquito net is estimated at US$0.0072, which is approximately 4,000 times cheaper than the least expensive commercial meshes [5]. In addition, the polyethylene polymer does not produce the intense inflammatory reaction observed with nylon. The polymer has been widely and safely used, but it requires specific sterilization techniques [22]. Interested parties should audit its use, preferably in a randomized fashion with as strict a follow-up as is feasible. The data so far, however, suggest that neither early infection nor later sepsis (as determined by the need for mesh excision) is commonplace. Many years have passed since Lichtenstein announced his novel approach, to the dismay of many in the medical establishment, to groin hernia repair. He would, no doubt be overjoyed that his concept might now reach many underprivileged patients throughout the world. It would seem that mosquito net meshes might prove to be more useful than previously considered.

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