Novel in Vitro Model for Assessing Susceptibility of Synthetic Hernia Repair Meshes to *Staphylococcus aureus* Infection Using Green Fluorescent Protein-Labeled Bacteria and Modern Imaging Techniques

Ihab Halaweish,¹ Karem Harth,² Ann-Marie Broome,³ Gabriela Voskerician,^{4,6}
Michael R. Jacobs,^{1,5} and Michael J. Rosen²

Abstract

Background: Mesh infection complicating hernia repair is a major cause of patient morbidity and results in substantial healthcare expenditures. The various constructs of prosthetic mesh may alter the ability of bacteria to attach and form a biofilm. Few data exist evaluating biofilm formation. Using the Maestro in-Vivo Imaging System (CRi, Inc., Woburn, MA) to detect green fluorescent protein (GFP)-expressing *Staphylococcus aureus*, we studied the ability of synthetic mesh to withstand bacterial biofilm formation in an in vitro model.

Methods: We included four meshes: Polypropylene (PP), polypropylene/expanded PTFE (PX), compressed PTFE (cPTFE), and polyester/polyethylene glycol and collagen hydrogel (PE). Five samples of each mesh were exposed to GFP-expressing *S. aureus* for 18 h at 37°C. Next, green fluorescence was measured using the Maestro Imaging System, with the results expressed in relative fluorescence units (RFU), subtracting the fluorescence of uninfected mesh (control). Each mesh subsequently underwent sonication and quantitative culture of the released bacteria, with the results expressed in colony-forming units (CFU). Analysis of variance was performed to compare the mean values for the different meshes.

Results: There was a statistically significant difference in bacterial fluorescence for the four meshes: PE (49.9 ± 25.5 [standard deviation] RFU), PX (30.8 ± 9.4 RFU), cPTFE (10.1 ± 4.0 RFU), and PP (5.8 ± 7.5 RFU) ($p = 0.001$). Bacterial counts also were significantly different: PE (2.2×10^8 CFU), PX (8.6×10^7 CFU), cPTFE (3.7×10^7 CFU), and PP (9.1×10^7 CFU) ($p < 0.001$).

Conclusion: Using novel imaging technology, this study documented significantly different amounts of *S. aureus* biofilm formation and proliferation on different mesh constructs, with good agreement between imaging and culture results. A multifilament woven mesh (PE) had the highest degree of biofilm formation. These findings are being evaluated in a clinical infection model.

THE USE OF SYNTHETIC MESH for ventral hernia repair has significantly reduced recurrence rates and is widely accepted by surgeons. However, complications from the widespread use of synthetic material can be serious. These complications include infection, recurrence, adhesions, erosion into adjacent structures, extrusion, and fistula formation. Recent studies have shown infection rates ranging from 0.7–2% in laparoscopic ventral hernia repair [1,2] and as high as 9–18%

in open inguinal and incisional hernia repair [3–5]. The presence of foreign material decreases the number of bacteria needed to cause infection by a factor of 10^4 [6]. Such infections are difficult to treat and may lead to the need for antibiotic therapy, extended hospitalization, or additional surgical procedures [7]. Most surgeons advocate removal of the prosthetic material in such cases [8], yet additional operations can increase morbidity with the possibility of injury to

¹Case Western Reserve School of Medicine, Cleveland, Ohio.

²Department of General Surgery, University Hospitals Case Medical Center, Cleveland, Ohio.

³Departments of Biomedical Engineering, Radiology, and Dermatology, Case Western Reserve University, Cleveland, Ohio.

⁴Department of Biomedical Engineering, Case Western Reserve University, Cleveland, Ohio.

⁵Department of Pathology, University Hospitals Case Medical Center, Cleveland, Ohio.

⁶Proxy Biomedical Limited, Spiddal, Ireland.

adjacent structures, hernia recurrence, or enlargement of the defect [4].

Some risk factors leading to synthetic mesh-related infections include a history of infection, as well as obesity, smoking, or bowel injury. Bacterial attachment, proliferation, and biofilm formation on the surface of synthetic materials are essential steps in the sequence leading to mesh infections [9,10]. In particular, *Staphylococcus aureus*, which often is present on the skin and form biofilms, is the organism most commonly associated with mesh infection [11,12]. Several mesh construct characteristics provide a more favorable environment for bacterial attachment and persistence.

Available synthetic meshes can be categorized on the basis of inherent characteristics such as porosity, weave, and water angle. Each of these unique structural components can have a great effect on the mesh surface area and chemistry and the ability of bacteria to adhere to the material. After bacterial adherence, the ability of the host immune system to eradicate the bacteria can be affected. Mesh science is an evolving field, and the perfect mesh is not within the current armamentarium of surgeons. Various approaches are found in the literature to evaluate bacterial adherence to and the propensity for growth on the current synthetic meshes [6,13–15]. Advances in both bacterial labeling and imaging technology have provided a unique and perhaps more accurate method for evaluating the relation between bacteria and biomaterials. Using novel imaging technology, we investigated how *S. aureus* adhered to various meshes in an in vitro model.

Materials and Methods

Bacterial preparation

We used a clinically isolated strain (Seattle 1945) of *S. aureus* transformed with a green fluorescent protein (GFP)-producing plasmid obtained from Dr. Mark Shirtliff. The plasmid had been constructed by inserting the promoter for the global regulator *sarA* into the upstream region of a promoterless GFP gene adapted for maximum expression in *S. aureus* [16]. The strain was recovered from -70°C storage and subcultured onto a blood agar plate incubated at 37°C for 24 h. An individual colony was then inoculated into 5 mL of Brain Heart Infusion (BHI) broth and incubated in a 37°C shaker at 200 rpm for 18 h. The inoculum used for mesh inoculation was prepared by diluting this overnight culture 1:100 in fresh BHI broth. Quantitative culture was performed to determine the size of the inoculum.

Experimental conditions

The synthetic meshes were classified according to the system of Amid system [17] and consisted of Motif[®] (cPTFE; Proxy Biomedical Ltd., Spiddal, Ireland), Parietex Composite[®] (PE; Covidien, Dublin, Ireland), Composix E/X[®] (PX; C.R. Bard, Covington, GA), and Visilex[®] (PP; Bard) (Table 1). According to a previously described model [18], five 2-cm samples of each mesh were placed individually in the wells of a 24-well plate. Each mesh was inoculated with 1 mL of the GFP *S. aureus* suspension described above. Five control samples were placed in 1 mL of sterile BHI. The meshes were then incubated for 24 h at 37°C . After 24 h, the supernatant liquid was aspirated, and the meshes were washed five times in 1 mL of 0.9% normal saline (NS). They were then transferred to sterile black 24-well plates (Genetix Ltd., New Milbank, U.K.) in 1 mL of 0.9% NS for quantitative fluorescence measurement. Stock solutions of BHI broth and NS were cultured to ensure sterility.

Quantitative biofilm fluorescence

Spectral fluorescence images were obtained using the Maestro[™] in-Vivo Imaging System (CRi, Inc., Woburn, MA). A band-pass filter appropriate for the fluorochrome of interest (GFP; E_x 445–490 nm, E_m 515 longpass filter; acquisition settings 500–720) was used for emission and excitation light, respectively. The tunable filter was stepped automatically in 10-nm increments while the camera captured images at an automatic exposure.

To evaluate signal intensities, regions of interest (ROI) were selected over the mesh areas, and the total fluorescence signal from those areas was determined. Total signal in the ROI in photons measured at the surface of the mesh was divided by the area of the mesh (in pixels) as well as the exposure time (in ms). The spectral fluorescent images consisting of autofluorescence spectra and GFP-*S. aureus* were captured and unmixed on the basis of their spectral patterns using commercially available software (Maestro; CRi). Spectral libraries were generated by assigning peaks to the background fluorescence (mesh), background from the imaging stage and plate, and fluorescence from GFP-expressing bacteria. The spectral libraries were computed manually using the Maestro software, with untreated mesh used as its own background control. All analysis was based on the spectral library determined from this spectral shift. Maestro signal intensities are represented as relative fluorescence units (RFUs).

TABLE 1. CHARACTERISTICS OF SYNTHETIC MESHES

Construct	Mesh type ^a	Material	Chemistry	Porosity	Water angle	Filament
Non-composite	I	MotifMesh [®]	Compressed polytetrafluoroethylene (cPTFE)	Macroporous	Hydrophobic	
Non-composite	I	Visilex [®]	Polypropylene	Macroporous	Hydrophobic	Braided monofilament
Composite	III	Parietex [®]	Polyester/polyethylene glycol and collagen	Macroporous	Hydrophilic	Multifilament
Composite	III	Composix [®]	Polypropylene/expanded PTFE (ePTFE)	Macroporous/microporous	Hydrophobic	Braided monofilament and PTFE

^aAccording to Amid's classification.

PTFE = polytetrafluoroethylene; cPTFE = compressed PTFE; ePTFE = expanded PTFE. See text for sources of brand name mesh materials.

Fluorescence microscopy

To confirm biofilm formation on the surface of the infected meshes, we used a Leica DMI 6000B fluorescence microscope (Spectronic Analytical Instruments, Garforth, United Kingdom) equipped with a fluorescein isothiocyanate filter, which allows detection of GFP. Fluorescence microscopy was used for confirmation of the presence and qualitative evaluation of biofilm, with uninfected mesh serving as control. Regions with greatest amount of biofilm were noted, and digital photographs were obtained at a magnification of 100 $\times$.

Biofilm quantitation

Following Maestro imaging and fluorescence microscopy, each mesh sample was placed in 10 mL of 0.9% NS in a sterile 15 mL conical tube. Biofilm was released by sonication for 5 min at 43 kHz using an ultrasonic waterbath (Model FS-9; Fisher Scientific, Pittsburgh, PA). Bacterial counts were then determined on the mesh sonicate by plating serial 10-fold dilutions in 0.9% NS in duplicate on blood agar plates. Bacterial growth obtained is expressed as colony forming units (CFU)/mesh sample. The lower detection limit is 3×10^3 CFU/mesh sample.

Data analysis

The average percent bacterial adherences measured by Maestro signal and bacterial release counts (CFU/mesh) were calculated for each mesh group. Analysis of variance (ANOVA) was performed to assess differences between mesh groups. A *p* value of ≤ 0.05 defined statistical significance. Followup post-hoc analysis was performed if differences were found. Data were analyzed using STATA software version 10.1 (StataCorp, College Station, TX).

Results

Quantitative fluorescence

Imaging of the mesh following a 24-h incubation and serial washes yielded the following fluorescence intensities across the mesh: (RFU $\pm$ SD [standard deviation]): PE (49.9 ± 25.5), PX (30.8 ± 9.4), cPTFE (10.1 ± 4.0), and PP (5.8 ± 7.5) (*p* = 0.001) (Fig. 1). Post hoc analysis revealed that PE had a significantly higher Maestro signal than cPTFE (*p* = 0.003) and PP (*p* = 0.001) but not PX (*p* = 0.33). There were no differences among cPTFE, PP, and PX.

Bacterial release counts after sonication

Bacterial counts released by sonication differed significantly among the meshes: PE (2.2×10^8 CFU/mesh), PX (8.6×10^7 CFU/mesh), cPTFE (3.7×10^7 CFU/mesh), and PP (9.1×10^7 CFU/mesh) (*p* < 0.001) (Table 2). Post-hoc analysis revealed that significantly more bacteria were released from PE than from PX (*p* = 0.007), PP (*p* = 0.01), and cPTFE (*p* < 0.001).

Fluorescence microscopy

Representative images of uninfected mesh compared with mesh exposed to *S. aureus* for 24 h are shown in Figure 1. The images represent areas where the greatest biofilm formation was present. These images were not used for quantitative purposes.

Discussion

The use of synthetic mesh for the repair of ventral and incisional hernias has reduced recurrence rates significantly. Unfortunately, the use of synthetic mesh can be complicated by infection despite aseptic technique and perioperative prophylactic antibiotics. When these complications occur, the surgeon and the patient are faced with a complex situation, often necessitating multiple surgical interventions. The exact incidence of this problem is understood poorly because of the lack of standardized definitions and reporting, but the condition likely occurs in as many as 10% of cases [19]. Several studies have noted that the number of organisms needed to cause an infection in the presence of foreign material is approximately 1/10,000 the number needed to cause skin infection [20]. *Staphylococcus aureus* is a common skin commensal and thus can be introduced easily into incisions and lead to infection [14]. The genus *Staphylococcus* is most prevalent of all the organisms associated with foreign-body infection because of the ability of most species to form biofilms [11,12]. Several technical and clinical risk factors can encourage mesh-related infections; the morphology and chemistry of synthetic materials also may influence the likelihood of infection. Using novel imaging technology and an in vitro mesh infection model, we demonstrated that the individual mesh construct may affect the ability of *S. aureus* to adhere to and form a biofilm on synthetic mesh.

Adherence of bacteria is an important step in mesh-related infections. The process of bacterial persistence on synthetic materials includes attachment and subsequent biofilm formation. Bacterial strains are less adherent and less pathogenic in the absence of biofilms [9,21]. Biofilm is formed following the attachment of a community of bacteria to a surface and subsequent release of an exopolysaccharide matrix. This "biofilm skeleton" protects the bacteria from antibiotics and the host defense system, thus facilitating persistent infections and challenging attempts to eradicate these infections [9,16,21–23]. Some of the factors influencing the initial efficacy of adherence to a biomaterial include the chemical composition, surface charge, hydrophobicity, surface texture, and three-dimensional physical configuration of the material [9]. The meshes used in our study allowed us to evaluate how mesh-related factors influence *S. aureus* attachment, proliferation, and biofilm formation.

Influence of wettability

The wettability or water contact angle of meshes influences bacterial attachment [24]. A material with a high contact angle is considered hydrophobic and potentially less attractive for attachment by certain bacterial strains. A material with a low contact angle is considered hydrophilic and perhaps more attractive for attachment by bacterial strains. We investigated one hydrophilic polyester-based mesh (Parietex Composite; Covidien) and three hydrophobic meshes—cPTFE (MotifMesh; Proxy Biomedical), PP (Visilex; Bard), and PP/PTFE (Composix; Bard). Each of these meshes falls within a spectrum of relative water contact angles, but they generally can be grouped as either hydrophilic or hydrophobic. The hydrophilic mesh we investigated had the greatest amount of biofilm, whereas two of the hydrophobic meshes had the least amount. The exception among the hydrophobic meshes was the dual-sided PP/PTFE mesh; we found no difference in

Mesh	Control	<i>S. aureus</i>	Maestro fluorescence signal intensity*
PE			49.9 ± 25.5
PX			30.8 ± 9.4
PP			10.1 ± 4.0
cPTFE			5.8 ± 7.5

* Average RFU (Relative Fluorescence Unit) $\pm$ standard deviation

PE = Polyester/polyethylene glycol and collagen; PX = PP/expanded PTFE; PP = Polypropylene; cPTFE = compressed PTFE; PTFE = polytetrafluoroethylene

FIG. 1. Representative images of uninfected mesh compared with mesh exposed to *S. aureus* for 24 h.

fluorescence signal from that seen with the polyester mesh. Prior studies have shown that *S. aureus* has initially less adhesion to highly hydrophobic meshes such as PTFE compared with the less hydrophobic PP [24]. However, with long-term exposure, this observation changes to stimulate bacterial

growth on hydrophobic meshes [25]. Other studies have noted contradictory results and reported that the hydrophobicity of materials enhances bacterial attachment [26–28]. Engelsman et al. showed that PTFE had the highest evidence of biofilm formation compared with various other mesh morphologies, including polyester [24], which differs from our findings. Some reasons that may explain the differences include the previous investigators' use of a longer exposure period (6 days vs. 1 day) and of a different approach to quantifying the presence of bacteria (confocal imaging of representative sonicate solution vs. quantitative fluorescence of the entire mesh surface with quantitative bacterial biofilm determination).

Influence of filament composition

Various three-dimensional filament compositions are found in meshes. The structure of filaments is distinctive, with some meshes having a monofilament structure whereas

TABLE 2. AVERAGE BACTERIAL COUNTS FOR VARIOUS MESH MATERIALS AFTER SONICATION

Mesh	Bacterial counts (CFU/mesh)
Polyester/polyethylene glycol and collagen	2.2×10^8
Polypropylene	9.1×10^7
Polypropylene/ePTFE	8.6×10^7
cPTFE	3.7×10^7

PTFE = polytetrafluoroethylene; cPTFE = compressed PTFE; ePTFE = expanded PTFE.

others have multifilament fibers. Some of the reasons there are various combinations of filaments in mesh include, but are not limited to, achieving greater strength, better tissue integration, and ease of use. The more complex the architecture, the greater the surface area of the material as well as the presence of niches that bacteria can use as a haven from tissue ingrowth, neovascularization, antibiotics, and the host inflammatory response [6,9]. It is estimated that the surface area of multifilament material is 157% higher than that of monofilament materials [6,24]. Other studies have shown that bacteria have a propensity to attach to and produce more biofilm in the niches between the filaments [25]. Interestingly, the nature of the braiding of the mesh seems to correlate with the location of bacterial attachment. In our study, fluorescence microscopy corroborated findings from other studies in that the majority of bacteria adhered in areas where mesh intertwined. Recently, Aydinuraz et al. evaluated the ability of *S. epidermidis* and *S. aureus* to adhere to various polypropylene constructs using an in vitro model [29]. In the *S. aureus* group, the investigators reported greater adherence to the monofilament antiadhesive-coated polypropylene relative to other multifilament polypropylene constructs. Given their different methodologies for both bacterial biofilm estimate (counts of bacteria released by vortex vs. sonication) and imaging (scanning electron microscopy vs. fluorescence-guided imaging), it is difficult to compare their results with ours. However, it appears that the antiadhesive coating on the polypropylene affects *S. aureus* attachment significantly. The remaining polypropylene materials, multifilament and monofilament, had similar bacterial counts, with the highest overall count being found on the multifilament polypropylene. We compared a varied group of materials, used two modes of bacterial estimates to quantify biofilm formation, and provided qualitative support with fluorescence microscopy. Additionally, we believe that quantitative fluorescence is a more accurate method for biofilm estimation, as it ensures quantification of all viable bacteria on the entire mesh surface.

Influence of porosity

The available surface area of mesh can be altered by the porosity of the material. Porosity, in particular microporosity, also provides niches where bacteria can hide from the host and antibiotics. Furthermore, micropores allow the penetration of bacteria but hinder entry of the larger macrophages and neutrophils [17]. In contrast, it is thought that macroporous meshes allow inflammatory cells to access these regions, thus making it more challenging for bacteria to become established [24]. The microporous nature of the PP/PTFE mesh we evaluated showed no difference from the macroporous polyester mesh on Maestro analysis but did have greater post-sonication bacterial counts than non-composite macroporous polypropylene. As discussed above, this result may in part also be attributable to the mesh exposure time chosen for our study.

Conclusion

Using novel imaging technology and a GFP-expressing clinical strain of *S. aureus*, we have shown that there are differences in bacterial biofilm formation on different mesh constructs. Further investigations through in vivo modeling

are necessary to understand how these relations are impacted by the host response, and such experiments are in progress in our laboratory.

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Author Disclosure Statement

Dr. Gabriela Voskerician is currently an employee of Proxy Biomedical Ltd. Dr. Michael Rosen is a consultant to and speaker for Lifecell, Covidien, Gore, and Cook.

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Address correspondence to:

Dr. Michael J. Rosen

Department of General Surgery

University Hospitals Case Medical Center

11100 Euclid Ave.

Cleveland, OH 44106

Email: Michael.Rosen@UHhospitals.org