Mastopexy is generally regarded as having only a temporary result and not a permanent outcome. As early as 1981, Johnson and later Goës, Sun et al., and in 2008 de Bruijn and Johannes reported good, permanent results and no recurrent ptosis with the use of polypropylene or polyester mesh. The last authors reported a series of 327 reinforced breasts (170 patients) with the longest follow-up, 4.5 years. Neither extrusion nor fibrosis was observed.

It has been shown that mesh does not hamper proper physical examination of the breast, nor does it interfere with radiographic (mammographic), ultrasound, or magnetic resonance imaging investigations. Mesh has been known for its safe use in medicine for over 40 years.

Recently, a system of three-dimensional, pre-shaped, feather-soft knitted polyester mesh implants in different sizes and concomitant sizers to facilitate implantation was introduced (Breform). The mesh implant acts as an internal bra, preventing recurrent ptosis (Figs. 1 through 4).

Although promising results have been reported based on clinical outcome and outside measurements, until now nothing has been known about the mechanical and physical behavior of mesh once it has been inserted and integrated into the female breast. Other than being safe and well tolerated, the ideal mesh implant should have the following characteristics: good integration in the breast; induction of some, but not too extensive, collagenous tissue; and enhancement of the overall strength. The composite is so strong that rupture or failure is extremely unlikely. The mesh composite shows high pliability, is therefore very supple and not palpable under the skin.

Background: Mastopexy is generally regarded as having only a temporary effect. To prevent recurrent ptosis, mesh has been inserted successfully and safely, without oncological drawbacks, for almost three decades. Recently, preshaped three-dimensional knitted polyester mesh in different sizes was introduced to reinforce the breast during mastopexy. Until now, however, the physical and mechanical characteristics of mesh inserted in the female breast were unknown.

Methods: Polyester mesh removed from breasts in which it had been implanted was subjected to mechanical tests (two implants) and histological examination (five pieces of implant).

Results: Mesh induces only a thin layer of collagenous tissue together acting as a composite material. The collagen increases the in-plane stiffness of the mesh and enhances the overall strength. The composite is so strong that rupture or failure is extremely unlikely. The mesh composite shows high pliability, is therefore very supple and not palpable under the skin.

Conclusion: Three-dimensional knitted polyester mesh appears to possess the proper mechanical characteristics to reinforce a ptotic breast during mastopexy. (Plast. Reconstr. Surg. 124: 1, 2009.)
fibrous tissue surrounding and reinforcing the mesh; a high in-plane stiffness and strength; and high pliability. The in-plane stiffness is the reciprocal of compliance (used in pulmonary physiology), which is a parameter of elasticity. The inserted mesh should have a low amount of elasticity and thus a high in-plane stiffness; otherwise, the mesh is unable to give the necessary support and reinforcement and maintain the desired shape. On the other hand, the integrated mesh should have high pliability to give a supple, soft, and natural breast, which gives way with touching and pressing. Inserted in the breast, the mesh is surrounded by a thin layer of connective tissue. This interwoven mesh and connective tissue act as a composite material. It is the mechanical and physical behavior of this composite that matters.

To investigate its physical characteristics, histological and mechanical tests of the composite material were performed. Our hypotheses were as follows:

1. The reactive collagenous tissue induced by the inserted implant and being interwoven with it contributes to the in-plane stiffness of the mesh, inhibiting the low-energy consuming shear deformation mechanism of the original mesh and enhancing the overall strength.
2. The composite material will have an ultimate tensile strength beyond forces normally exerted on the human body, preventing it from rupturing.
3. The composite material remains supple.

PATIENTS AND METHODS

We inserted soft-knitted three-dimensional polyester mesh (Breform) in 121 breasts (63 patients), so far with the longest follow-up of 2 years. Aided by sizers, insertion of mesh is technically not
difficult. Normal physical, radiographic, and magnetic resonance imaging examinations of the breasts remained unrestricted.\(^\text{17}\) No major complications or extrusion occurred. No recurrent ptosis was noted (Table 1). In four patients, a minor secondary cosmetic correction was performed that enabled us to harvest a piece of inserted mesh for histological examination 6 to 18 months postoperatively. In one patient, all of the mesh was removed in both breasts 15 months postoperatively at her request because of unexplained pain complaints. This patient also had pain in her breasts preoperatively. After removal, the pain remained unchanged. She regretted the removal afterward, as the shape of the breasts, deprived of the reinforcing mesh, deteriorated. So far she is the only patient who has undergone implant removal. In all other patients, the implants are still in place. It was noted that implant removal was technically easy, and the implants were still in place where they originally were inserted 15 months earlier, fixed on the fascia of the pectoralis, serratus, and rectus muscles, interwoven with only a thin layer of connective tissue surrounding the breast gland as an internal bra (Figs. 5 and 6). The removed implants were used for histological examination as well for physical mechanical testing. They were submitted to tensile strength and pliability testing, and the outcome was compared with the results of testing of the original plain, unused polyester mesh (e.g., the implants before operation). The removed implants were tested immediately after explantation.

After inspection and manipulation of the structure, four directions were chosen as material testing directions: two “principal” directions, directions 1 and 2, and two “shear” directions, directions \(\gamma_1\) and \(\gamma_2\) (Figs. 7 and 8).

Directions 1 and 2 are the directions in which the structure contains continuous lines of fiber material. The structure behaves relatively stiffly in these directions and will mainly show uniaxial

Table 1. Patient Data and Complications

<table>
<thead>
<tr>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Patient data</td>
</tr>
<tr>
<td>No. of patients</td>
</tr>
<tr>
<td>Average age, years (range)</td>
</tr>
<tr>
<td>Operated breasts</td>
</tr>
<tr>
<td>Contralateral procedures after reconstruction</td>
</tr>
<tr>
<td>Otherwise unilateral procedures</td>
</tr>
<tr>
<td>Longest follow-up, years</td>
</tr>
<tr>
<td>Complications in 121 breasts</td>
</tr>
<tr>
<td>Local infection responding well to antibiotics</td>
</tr>
<tr>
<td>Abscess needing evacuation</td>
</tr>
<tr>
<td>Hematoma needing drainage</td>
</tr>
<tr>
<td>Deformity needing minor secondary revision</td>
</tr>
<tr>
<td>Loss of nipple sensation</td>
</tr>
<tr>
<td>Extrusion</td>
</tr>
<tr>
<td>Capsular contraction</td>
</tr>
<tr>
<td>Recurrent ptosis</td>
</tr>
</tbody>
</table>
strain at small deformations. Small deformations of the structure in directions $\gamma_1$ and $\gamma_2$ will mainly cause rotation of the principal directions, hence the term shear directions. The open structure will become denser when pulling in these shear directions. The apparent stiffness in these directions will be relatively low, until the fibers start to align with the pulling direction, and the stiffness will increase significantly at larger deformations. This is a common physical behavior of all biaxial mesh material.

All tested specimens measured $60 \times 30$ mm and aligned with directions 1, 2, $\gamma_1$, and $\gamma_2$ (Fig. 9). Testing of the original material was conducted in a twofold manner. Tests in four directions with the removed implants were performed once because of limited material. The specimens were submitted to (1) in-plane stiffness tests, (2) ultimate tensile strength tests, and (3) pliability tests.

**In-Plane Stiffness Tests and Ultimate Tensile Strength Tests**

These tests were performed on a Zwick Roell tensile tester with two different load cells. A load cell with a capacity of 50 N (accuracy $<0.05$ N) was used to measure the in-plane stiffness of the specimens at small deformations and pliability, and a 1000-N load cell (accuracy $<1$ N) was used to test ultimate tensile strength. After clamping, the tensile tester stretches the material by moving the lower clamp downward while measuring the required force for this movement (Figs. 10 and 11). The displacement was measured using a Heidenhain optical encoder, which has an accuracy of 1.0 $\mu$m.

**Pliability Tests**

The pliability of the composite material appeared too high to be measured using a standard three-point bending test. In other words, it was too flexible and pliable. Instead, the pliability was measured using the forces of gravity. The material

![Fig. 8. The four testing directions.](image)

![Fig. 9. Specimens taken from the explanted mesh in directions 1, 2, $\gamma_1$, and $\gamma_2$.](image)

![Fig. 10. Tensile tests of the original material in direction 1, (left) at the initial situation and (right) after displacement.](image)
was horizontally clamped at one side, leaving a 30-mm-long, 30-mm-wide, 3-mm-thick strip hanging freely in the air. The strip deflects due to the weight of the material. A picture was taken of the deflected shape and analyzed using dedicated software, which extracts the strip curvature from the image. By assuming a density of 1150 kg/m³, the internal bending moment due to gravity can be calculated at each point of the strip. These two parameters, internal bending moment and curvature, were used to calculate the bending stiffness. Bending stiffness is the reciprocal of the pliability.

RESULTS

In-Plane Stiffness

Force-displacement curves were created from the obtained experimental results indicating the in-plane stiffness of the original material and the removed composite material (Fig. 12). The curves

![Fig. 11. Tensile tests of the removed implants in direction 1, (left) at the initial situation and (right) after displacement.](image)

![Fig. 12. Force displacement curves for the original material and the removed composite material.](image)
for the principal directions 1 and 2 of the original material immediately showed a material response when strained at small deformations, which we defined as deformations smaller than 5 mm. As expected, pulling in these directions immediately loaded the fibrous material and showed a uniaxial strain. As explained above, pulling in the shear directions γ1 and γ2 indeed first caused rotations of the fibers before the loading of fibrous material started. The response was delayed. The findings apply both for the original material and for the removed composite material. From these curves, it is clear that the in-plane stiffness of the mesh increased significantly in all directions when reinforced with collagenous tissue. On average, the stiffness increases more than 86 percent at a tensile load of 2.5 N, a typical loading situation in practice (see Discussion) (Table 2).

In-Plane Strength

For testing the in-plane strength of the original material, new specimens were used. To test the removed composite specimens, the same material previously used for the stiffness evaluation was used because no more material from the removed implants was available. Therefore, comparing the stiffness of both curves was not valid, as the composite specimens had already been stretched. The ultimate strength, the load at which the specimens rupture, could still be compared. Figure 13 shows the results of the strength tests of the material in principal direction 1 and shear direction γ2, which were similar to the outcomes of tests in directions 2 and γ1.

The ultimate strength is represented by the serrated peak of the displacement curves. The strength of the two kinds of material did not change significantly for shear direction γ2, but there was an increase in strength (height of the peak) in the composite material for principal direction 1. The first signs of failure were visible at loads above 60 N. Rupture occurred at 100 N for a force in direction 1 and 75 N for direction γ2.

Table 2. Apparent Stiffness of the Specimens at a Load of 2.5 N, a Typical Load for Composite Material during Normal Physical Activity

<table>
<thead>
<tr>
<th>Direction</th>
<th>Original Material (N/mm)</th>
<th>Removed Composite Material (N/mm)</th>
<th>Increase (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.65</td>
<td>1.31</td>
<td>102.2</td>
</tr>
<tr>
<td>2</td>
<td>0.48</td>
<td>0.79</td>
<td>64.6</td>
</tr>
<tr>
<td>γ1</td>
<td>0.23</td>
<td>0.57</td>
<td>142.6</td>
</tr>
<tr>
<td>γ2</td>
<td>0.18</td>
<td>0.24</td>
<td>36.3</td>
</tr>
<tr>
<td>Average</td>
<td>0.39</td>
<td>0.73</td>
<td>86.4</td>
</tr>
</tbody>
</table>

Pliability

The bending stiffness of the strip was calculated at 1.5 · 10−6 N/m2, comparable to the bending stiffness of ordinary household aluminum foil. This indicates that the composite material is highly pliable.

Histology

The histological reports of five different patients showed the same results: mesh embedded in adipose tissue surrounded by a thin layer of reactive collagenous tissue and a very mild inflammatory reaction. There was no difference between mesh inserted for a period of 6 months and that inserted for 18 months (Fig. 14). Figure 7 shows the macroscopic appearance, which was equal in all five patients.

DISCUSSION

In-Plane Stiffness

The in-plane stiffness, reciprocal to the amount of elasticity, increases an average of 86 percent through the ingrowths of reactive collagenous tissue. This increased stiffness is favorable for a mesh breast implant, as high in-plane stiffness is desired to keep the breast in shape in various natural circumstances. The ingrowths of collagenous tissue give the implant the properties of a composite material. From materials science, it is known that composite materials are usually stronger than the sum of their components. This probably applies in the human body with mesh implants as well.

The in-plane stiffness of the specimens varies significantly, depending on the load. To estimate the region in which the material will be loaded in practice, a simple equation is used: suppose a breast weighs 0.5 kg. This corresponds to a load of approximately 5 N when the human body is at rest. Assuming that the entire load has to be carried by the composite material with a width of 120 mm at the top side of the breast (an average Breform mesh implant, four times the width of our tested specimens), the load per millimeter width is equal to 1/24 N/mm. Translated into our testing conditions, this corresponds to the point at which the applied load is 1.25 N. During walking, body accelerations typically vary around 2 g, two times the force of gravity. For analyses of the experimental results, this indicates that an applied force of 2.5 N in the experimental setup corresponds to a typical loading situation in practice. The apparent in-plane stiffness of the composite at this load can be extracted from the curves by dividing the force...
of 2.5 N by the corresponding displacement. In practice, this means that under normal conditions there will be only very little stretching of the composite material.

**Tensile Strength**

The first signs of failure are visible at loads above 60 N. Returning to the loading example described above, this corresponds to a body load of 48 g. This is far above the lethal limit for a human being, indicating that the implants are strong enough to withstand any load that will be exerted during the lifetime of the patient. It should be mentioned that in all tests rupture occurred at the fixation points of the specimens, the weakest points artificially, indicating that the real tensile strength of the material unaffected by clamps is even stronger. Implant rupture, therefore, is extremely unlikely under normal physical circumstances.

**Pliability**

The outcome of this test showed that the composite material, although it had a high in-plane stiffness, was still extremely pliable, and thus supple. This outcome corresponded with the clinical observation that all 121 reinforced breasts remained soft and supple and that the polyester mesh implants could barely be felt, except in rare cases.

**Histology**

In our series, we did not encounter any cases of hardening or any clinical impression of fibrosis or capsular contraction, as with breast augmentation. All breasts remained supple. All five histologic specimens showed precisely the same outcome, with only a thin layer of collagenous tissue surrounding the mesh. Combining these observations and results, we assume that the histological findings are truly representative for all reinforced breasts. It is very likely that the ingrowth of just a
thin collagen layer is the characteristic feature of implanted polyester mesh in the female breast.

The mechanical tests in this study were performed on mesh implants removed from only one patient 15 months postoperatively. As discussed above, we have no reason to assume that this case is not representative for all patients with a polyester mesh reinforcement of the breast. Future studies are needed to confirm this.

CONCLUSIONS

The reactive collagenous tissue surrounding the mesh, together acting as a composite material, contributes to the in-plane stiffness of the mesh, with an average increase of 86 percent, and enhances its overall strength. The composite material has an ultimate tensile strength or breaking point at forces far beyond the lethal limits for a human being. Rupture under normal living conditions is, therefore, extremely unlikely. The composite mesh-collagen material shows high pliability, indicating that it is very supple indeed. This finding coincides with the clinical observation that in our series of 121 breast reinforcements, the polyester mesh implant was not palpable. All histological examinations showed the same reassuring results: mesh was embedded in only a thin layer of collagenous tissue. No thick fibrosis was encountered. Preshaped, three-dimensional, knitted polyester mesh appears to possess the proper mechanical characteristics to reinforce a ptotic breast during mastopexy.

Hans P. de Bruijn, M.D., Ph.D.
Medisch Spectrum Twente
P.O. Box 50000
7500 KA Enschede, the Netherlands
hp.debruijn@tiscali.nl

REFERENCES


AUTHOR PLEASE ANSWER ALL QUERIES

AQ1: AUTHOR—Please supply the name and city/state location of the maker of Brefom, per Journal style for use of brand names.

AQ2: AUTHOR—Ref. 18: Please supply location of Chapman and Hall.