Implant Testing and the "Strain Energy" Concept

David A. Caplin, MD

St. Louis, Mo.

Summary: Benchtop performance test methodologies differ between manufacturers as regulatory agencies often leave the interpretation of testing standards up to manufacturer discretion, resulting in an inability to directly compare implants across manufacturers. Furthermore, traditional benchtop test methodologies focus on mechanical performance standards to address objective endpoints such as shell strength. However, other more difficult to define clinical performance requirements such as softness and natural feel are often difficult to measure via these methods. This review aims to discuss the evolution of breast implant testing standards, discuss the discrepancies in benchtop characterizations of implants, and highlight one manufacturer's novel approach to utilizing benchtop methodologies to quantify previously subjective endpoints such as firmness and natural feel and define their clinical relevance. (*Plast. Reconstr. Surg.* 142: 12S, 2018.)

Since the first accounts of the use of Silastic gel breast implants, developed by Cronin and Gerow, the goal of creating an implant with a natural feel has been of paramount importance to clinicians and manufacturers alike.[1] As such, novel breast implants designed to address limitations in the softness of the gel, thickness, and texture of the shell and gel diffusion have been developed over the past 60 years. These innovations in implant technology have been accompanied by additional regulatory scrutiny and increased performance demands from physicians and patients desiring an implant with more natural firmness and feel. To meet regulatory and clinical demands, testing standards have evolved resulting in significant innovations in the mechanical testing of breast implants.[2] Many of these benchtop test methodologies, however, are not standardized across manufacturers and thus, as each manufacturer generates its own specific data, comparisons across devices are difficult to make. Additionally, a critical limitation to benchtop testing standards is that they are an imperfect surrogate for evaluating the complex clinical and patient-specific performance characteristics of these devices in vivo. While these tests have been adapted to provide data that can be extrapolated to represent objective endpoints such as rupture and gel bleed, what remains elusive is the ability to objectively quantify subjective endpoints, such as firmness and natural feel.

BRIEF HISTORY OF BREAST IMPLANT INNOVATION

Despite the many noteworthy changes in breast implant technology, 2 key design components are still the most critically important: (1) the silicone gel filler; and (2) the silicone elastomer shell. Each of the 5 generations of breast implants that have been introduced into the U.S. market since the 1960s has iterated upon these 2 basic components.[3] Thick elastomer outer shells and thick firm gel used in first-generation silicone implants were eventually replaced with thinner more pliable shells filled with less cohesive gel to create a more natural feeling implant. These newer implants, which were used until the mid-1980s, were plagued by safety concerns such as shell failure and gel bleed.[4] These concerns led to the development of a third generation of breast implants, which paired thicker and more durable shells with a protective barrier layer intended to minimize gel bleed.[5] These early generations of silicone breast implants were grandfathered in prior to increased U.S. Food and Drug Administration (FDA) regulation and, therefore, allowed to remain on the market. However, increasing public and scientific scrutiny, coupled with the 1976 establishment of formalized FDA jurisdiction

From the Washington University School of Medicine and Parkcrest Plastic Surgery.
Received for publication April 12, 2018; accepted July 12, 2018.

DOI: 10.1097/PRS.0000000000004998

Disclosure: *Dr. Caplin is a clinical investigator for and consultant to Mentor Worldwide LLC. No financial support was obtained or granted for authoring this article.*

over the review and approval of these devices, ultimately led to the regulation and classification of breast implants as Class III devices requiring a Premarket Approval (PMA) application in 1988 and accordingly the need for high-quality clinical data.[4,6] These data were required to establish the safety and efficacy of the devices and, ultimately, led to the 1992 FDA moratorium on the use of silicone-filled breast implants restricting their implantation to subjects enrolled in clinical studies of the 2 remaining manufacturers: McGhan Medical Corporation and Mentor Corporation.[7] This heightened scrutiny on the design and performance of these implants led to the innovation of fourth and fifth generation implants, which include cohesive and highly cohesive gels and a myriad of round and anatomic shapes.

MECHANICAL TESTING STANDARDS AS AN INPUT TO BREAST IMPLANT REGULATORY APPROVAL

Coupled with the increased scrutiny of clinical data, the FDA refined their position on the mechanical analyses of silicone implants to include tests aimed at mimicking in vivo conditions whenever possible.[8] As a way to ensure quality control, mechanical testing standards were introduced and refined primarily to address concerns that developed as a result of the moratorium on silicone gel breast implants in the United States (which lasted from 1992 to 2006)[9] and following the discovery of user safety issues linked to Poly Implant Prosthesis (PIP) breast implants in 2010.[10] In the former situation, new fourth-generation breast implants were created with more viscous or cohesive gel that contained a greater degree of cross-linking to address previous concerns about gel bleed and migration.[4] In the latter, the substantial increase in the removal rate of PIP implants from 2011 to 2012 led to an increase in the number of biodurability studies to identify the causes of failure of the PIP devices.[10]

The testing of PIP devices has become a classic example of the utility of mechanical testing of implants and the importance of one's ability to compare outcomes across manufacturers in the interest of patient safety. When test results for PIP implants were compared with an unidentified brand of currently marketed implants, the unnamed implants showed much less variation (ie, lower SDs) and were within the industry designated specifications unlike the PIP implants that failed to meet these standards.

FDA's most current guidance encompasses testing for fatigue rupture, valve competency, cohesivity, gel bleed, stability, and shelf life. Specifically, for the fatigue rupture testing of the total device, FDA recommends cyclic testing to generate the resulting endurance load level, clinical relevance of the endurance load level, AF/N curve (AF/N is applied force versus number of cycles to failure), and all resultant raw data. Valve competency testing requires testing in accordance with American Society for Testing and Materials (ASTM) F2051 and destructive testing including burst pressures, failures modes, and rationale as to why the burst pressure results are clinically relevant. Cohesivity testing requires testing in accordance with ASTM F703 consisting of gel cohesion evaluation using the cone/pendant method and penetration testing. Bleed testing requires testing in accordance with ASTM F703 and additional gel bleed bench testing based on a protocol that mimics in vivo conditions. Stability testing is required to assess the effects of time and temperature (including elevated temperature). Lastly, shelf life testing of representative and aged samples is required through mechanical testing including ultimate elongation, join, tensile set, break force, valve competency, and gel cohesivity in addition to packaging testing to test the initial package integrity and the maintenance of packaging integrity (Section 6 Mechanical Testing) of the FDA Guidance for Industry and FDA Staff for Saline, Silicone Gel and Alternative Breast Implants; Issued November 17, 2006). While FDA has directed the types of analyses to be completed as part of a breast implant PMA submission, the choice of methodology has been left to the manufacturers with adequate latitude provided for the accounting of manufacturer-specific device characteristics. Outside of the United States, physical testing to predict the adequacy of device response to physiological and pathological stresses, undesirable conditions and forces, long-term use and potential failure modes, often performed per International Organization for Standardization 14607 are required elements for CE marking and other health authority submissions. Specifically, International Organization for Standardization 14607 focuses on mechanical testing and physical evaluation. However, similar to FDA guidance, standards for testing protocols are often left open to manufacturer interpretation if adequate justification is provided. Although this leeway is advantageous in that it allows each manufacturer to refine and create specific tests best suited for their devices, it results in a lack of standardization across manufacturers.

This lack of standardization occurs in both the pre- and postmarket evaluations of breast

implants and impedes the ability to make direct and objective comparisons between implants of different manufacturers and accurately interpret the utility of mechanical testing as a predictor of clinical performance. Specifically, in addition to safety and efficacy, areas of interest include defining clinical benefits of gel cohesiveness, surface texture, and the differentiating properties of various implants, which remain a major concern of physicians and patients.

TRADITIONAL BENCH TO BEDSIDE INNOVATION OF BREAST IMPLANTS

In response to the regulatory requirements discussed in the preceding sections, traditional bench to bedside innovation of breast implants has focused on the identification of a potential harm, hazard, or clinical concern and the creation of implants that address these concerns in vitro as shown by mechanical testing within a specified range of acceptance criteria. Devices that did not meet these criteria were not advanced through innovation pipelines and those that did were submitted for clinical testing. While understandably these tests focused heavily on the standards set forth by health authorities, unaccounted for in this testing schema, however, is the ability to replicate all clinically relevant endpoints within the laboratory. For example, the compression of a breast implant along a single axis, to determine fatigue rupture rates, although informative, does not capture the complex mechanical, physiological, and anatomic nuances created by placing a breast implant in a tissue pocket and subjecting it to varying physical forces, from all directions, over the lifetime of the device.

Although primarily a regulatory endeavor, enterprising clinicians have made attempts to utilize mechanical testing to distinguish, characterize, and define what have traditionally been intangible clinical benefits, such as the firmness of an implant or the difference between varying amounts of fill volume (ie, fully- filled versus underfilled) and their influence on desired clinical outcomes.[11] A study by Kinney et al.,[2] measured differences in (1) gel elasticity; (2) gel compression; (3) shell-gel peel testing measuring the bond between the gel and the shell as well as a (4) morphological analysis of implants measuring the performance of the implant, as a whole, in the body among the major breast implant manufacturers in the United States. The authors suggested that the ideal implant is a combination or balance of these mechanical properties. For example, when evaluating the strength and structural integrity of the implants, smooth round implants required slightly less force to fracture the gel (average, 27.6 lb-f) compared with textured shaped implants (average, 37.0 lb-f). Additionally, a comparison between the gel elastic stretch in Sientra, Mentor and Allergan smooth round implants (average, 6.56 mm) showed that elastic stretch was greater than those observed in the corresponding shaped textured implants (average, 3.62 mm), suggesting that the smooth round implants have more gel elasticity and therefore should feel softer than the shaped textured devices. It is important to point out that while this refers to the implant, the elastic stretch test was only done on the gel and the observed softer feel of an implant is likely a result of the shell thickness, gel properties as well as the amount of gel in the shell. Studies such as these have highlighted how critical it is to attempt to utilize mechanical testing to better understand if and how the physical properties of these devices change over time once implanted.[12]

NOVEL APPROACH TO BREAST IMPLANT INNOVATION

Recent refinements to the understanding of the scientific properties of breast implants has led to the creation of novel approaches to breast implant design and manufacturing. Previously difficult to quantify unmet clinical endpoints, not mandated by health authorities for product approval, have now become the focus of mechanical testing. One manufacturer, Mentor Worldwide, LLC, has utilized these new insights to take a novel approach to breast implant innovation. In essence, Mentor has reverse engineered their newest device, MemoryGel Xtra Silicone Gel-Filled Breast Implants, by creating unique mechanical test methodologies to quantify previously subjective endpoints and by using those inputs to further refine their devices. What follows is an insight into this process; however, it is important to point out that these novel approaches are considered experimental methodology. Future contemplation of these methodologies to evaluate implants is required, along with additional testing and consensus across manufacturers before they can be considered industry standards.

With the creation of MemoryGel Xtra Breast Implants, Mentor aimed to provide a soft, more natural feel while not compromising the fullness achieved with higher cohesivity implants. This was accomplished by focusing on 3 specific implant properties: shell, gel, and fill. By filling their

shells to a greater degree than in previous generations and by utilizing a silicone gel filler, which is less highly cross-linked than MemoryShape and Inspira implants, Mentor created an implant that provided fuller implants with greater projection in the same shell styles with a more natural feel. To quantify that these implants satisfied this unmet need, however, Mentor Worldwide, LLC initiated several benchtop testing strategies that compared MemoryGel Xtra to both its own MemoryGel Breast Implants and its competitors.

As the focus of the engineering of these implants included the properties conferred by combining Mentor shells with their proprietary gel and novel fill volumes, Mentor devised tests to measure the effect of each of these components in part and as a whole. Specific to the shells, the strength and thickness of shells was assessed by shell tension and elongation testing (Fig. 1). Specific to the gel and fill volumes, the firmness of the implants was assessed in a manner that mimics an implant's in vivo environment through vertical and lateral compression tests. For vertical compression testing, implants were compressed by plates at their apex and base to a target force (lbf), and the displacement (inches) traveled were analyzed as a measure of firmness (Fig. 2).

Fig. 1. Shell tension and elongation test.

However, because this does not provide a direct indication of the performance characteristics of the implants due to variation in geometry (projection and width) among the implants, the strain energy density of each implant was also assessed during compression testing. The lateral compression test, used as a surrogate for a Pinch Test, was performed to mimic the user's tendency to assess stiffness of implants using fingers (Fig. 3). The pinch test measured the same parameters as the vertical compression test and was conducted by compressing the sides of the implant as opposed to the apex and base. For the duration of the test, the equipment continually measures and records the amount of force needed to laterally squeeze an implant and compress it by one-third of its original diameter. Higher forces required to achieve this degree of compression indicate greater firmness. As there is only 1 other manufacturer with a comparable fully filled technology currently on the market, comparative tests were initially conducted in a head-to-head manner with those devices.

When looking at shell thickness and shell strength, the shell of MemoryGel Breast Implants was 35% thinner [in a head-to-head shell thickness measurement of a representative sample of MemoryGel (n = 10) than Natrelle Inspira Breast Implants (n = 10)] and had a 30% higher tensile strength [in a head-to-head testing according to industry standard ASTM D412 test method for rubber properties in tension (v. 0901) between MemoryGel (n = 10) and Natrelle Inspira Breast Implants (n = 10)] (Mentor Implant Shell Mechanical Properties between Allergan Natrelle and MemoryGel Xtra - August 2017). Taken together, these data suggest that Mentor has effectively engineered a stronger yet thinner shell than their competitors, which may affect the overall

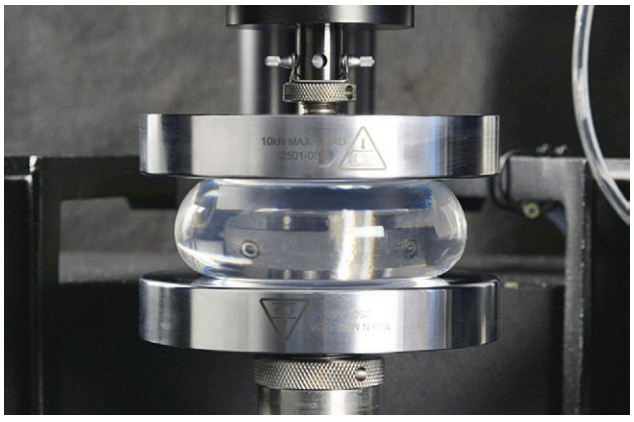

Fig. 2. Vertical compression test.

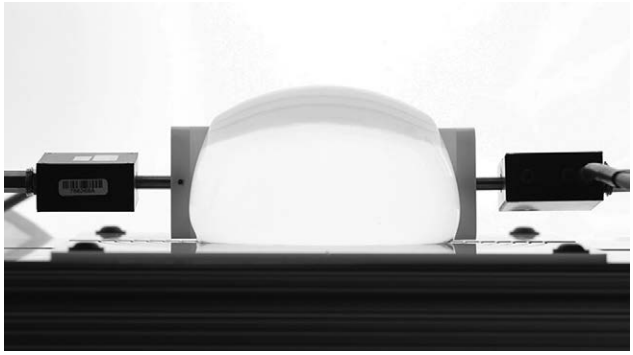

Fig. 3. Lateral compression test.

"softness" and "natural feel" of the implant as thicker shells may cause the implant to feel less "natural".

Results from the firmness evaluation study, which employed vertical and lateral compression tests, show that in a lateral compression, or pinch test, MemoryGel Xtra Moderate Plus Profile Breast Implants are firmer than the current MemoryGel Moderate Plus Smooth Breast Implants and thus capable of storing more Strain- Energy [Mentor R&D Benchtop Testing (Pinch Test) - July 2017] (Figs. 4 and 5). The concept of strain energy is defined as the energy stored in a body due to deformation. When subjected to an external loading force, the surface of the silicone implant distorts and lengthens in direct proportion to the amount of force that is applied. Similar to a spring, regardless of spring size, the more you compress it, the more it pushes back. This is a result of increasing strain energy. A similar concept can be applied to implants as, at a particular amount of deformation or compression, a specific amount of stored energy or pushback is created. The stored energy is then converted to kinetic energy, which allows the implant to return to its original configuration. The greater the amount of strain energy stored, the greater the implant's ability to resist permanent deformation that can be caused by external soft-tissue forces. In a similar, head-to-head vertical compression benchtop testing (Strain-Energy testing) comparing High and Medium profile fully filled implants compressed to 40 lbs and 30 lbs, respectively, MemoryGel Xtra Breast Implants (n = 4) provided comparable firmness to a competitor product (n = 3; Fig. 6). This benchtop comparison between the MemoryGel Xtra Breast Implants and competitor product illustrates comparable resistance to compression. The concept of strain energy is clinically relevant to breast implants particularly when they are subjected to increased soft-tissue pressure (eg, tight pocket, capsular contracture, tight inframammary folds). In these cases, there is a clinical need for the implant to maximally resist these external forces. One might expect that more highly cross-linked cohesive devices should be better able to

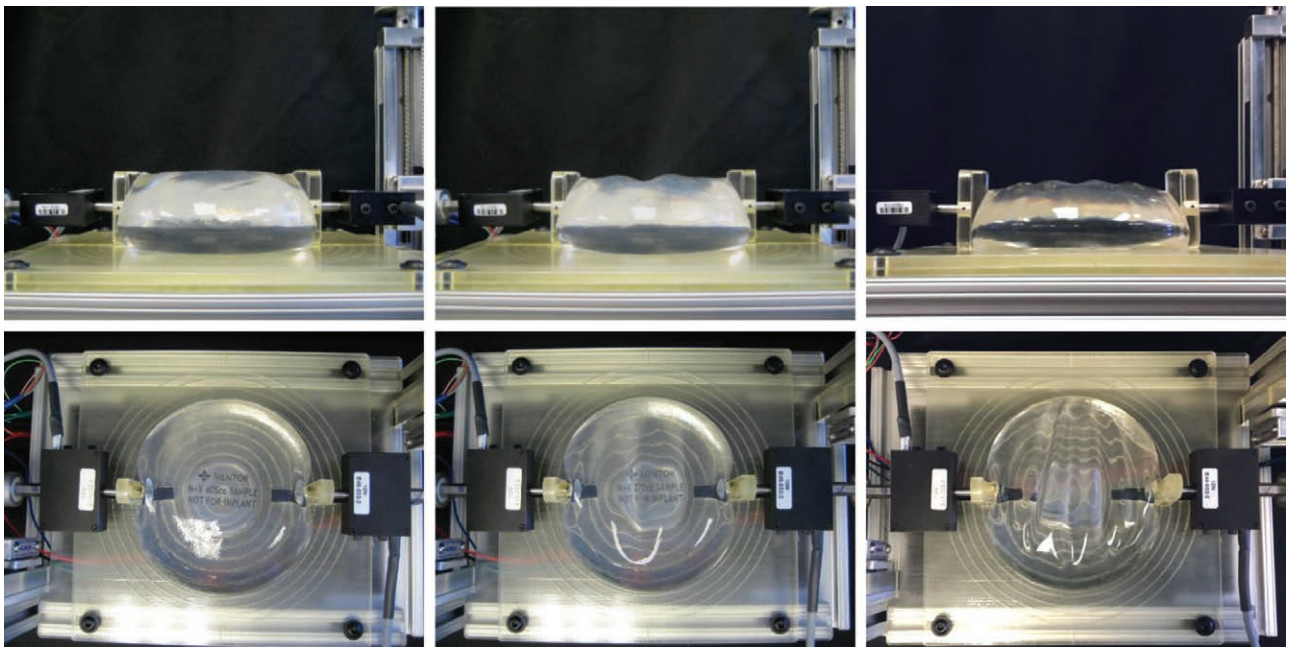

Fig. 4. Side and overhead views of Mentor MemoryGel Xtra Moderate Plus Profile 405 cc breast implants (*left column*), Mentor MemoryGel Xtra Moderate Plus Profile 370 cc breast implants (*center column*), and Mentor MemoryGel Moderate Plus Profile breast implants undergoing lateral compression testing (*right column*).

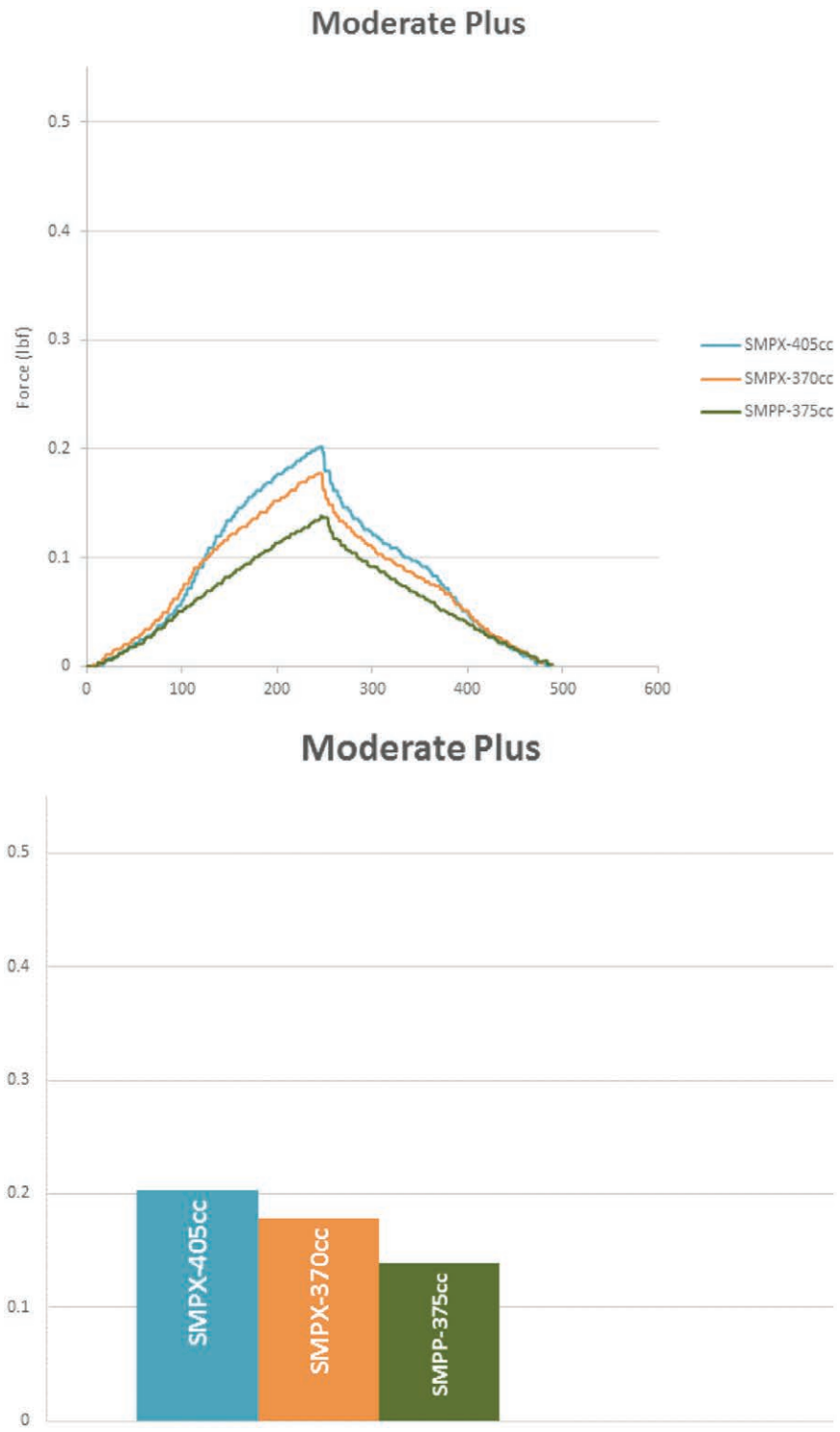

Fig. 5. Lateral compression test results comparing Mentor MemoryGel Xtra Moderate Plus Profile (SMPX) 405 cc and 370 cc to MemoryGel Moderate Plus Profile (SMPP) 375 cc demonstrating that MemoryGel Xtra Moderate Plus Profile implants are firmer than the current MemoryGel Moderate Plus implants.

resist deformation due to higher strain energy storage values. The most recently completed tests performed by Mentor Worldwide, LLC to validate these hypotheses show that when comparing implants of similar volume (245 + 5 cc) at 22.2 N (about 5 lb-f) of compressive force Smooth

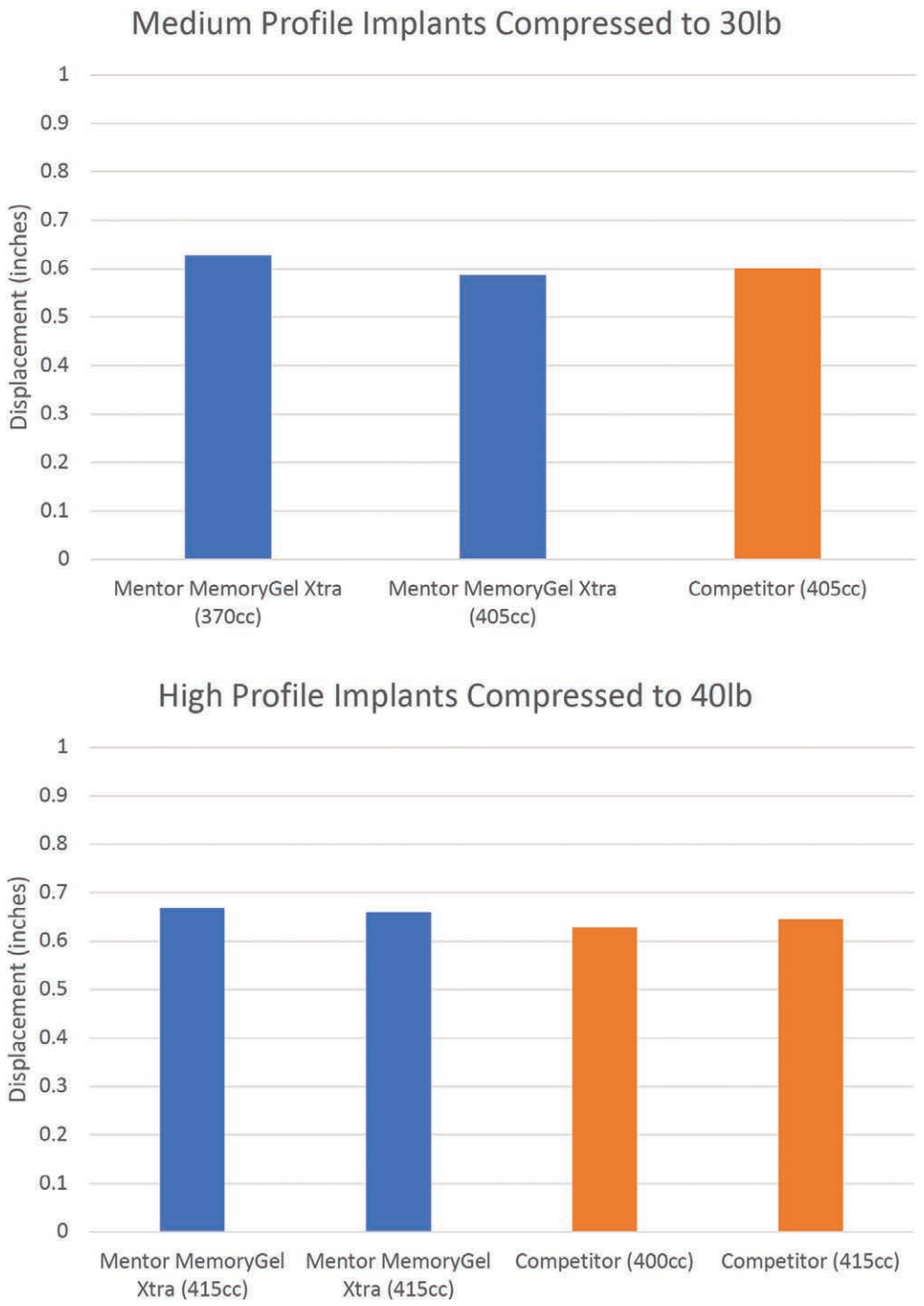

Fig. 6. Vertical compression benchtop testing (Strain-Energy testing) comparing High and Medium profile fully filled implants, compressed to (*above*) 30 lbs, and (*below*) 40 lbs, respectively.

MemoryGel Xtra (CO I) and the closest comparable MemoryShape (CO III) devices stored the same amount of strain energy on average (0.041 J) while the comparable Smooth MemoryGel Moderate Plus (CO I) device stored significantly less strain energy (average, 0.030J). Based on these test data, it appears that the higher strain energy stored in the Smooth MemoryGel Xtra M+ device (compared with the Smooth MemoryGel M+ device) comes from the increased recruitment of the shell in resisting deformation. The elasticity of the shell plays a greater role in energy storage for the fuller filled device at a given load. Additional testing is certainly needed, but it is evident that there are factors beyond cohesivity alone that influence implant strain energy storage potential.

The ultimate question becomes, how do these shell and Strain-Energy properties affect the clinical performance of "fully-filled" implants. In much the same fashion that a trampoline stores Strain-Energy (also called potential energy) during downward displacement as a child lands on its surface, breast implants have a similar ability to store energy when they are compressed by an external force such as a dynamic pectoralis muscle, an inelastic skin-muscle flaps, or a tight periprosthetic capsule. In the case of a trampoline, that stored potential energy (Strain-Energy) is converted to kinetic energy as the child is launched skyward. In much the same fashion the energy stored in a compressed breast implant converts to kinetic energy, which pushes outward and allows the implant to define the shape of the breast. Many surgeons have found that this has been best accomplished with highly cohesive gel implants, given their unique resistance to deformation but at a price: increased implant firmness. The resistance of these implants to deformation in the face of external soft-tissue pressure has made them not only a great choice for primary augmentations and reconstructions but also a very favorable choice in more challenging revision cases. As an example, when lowering of the inframammary fold is clinically indicated, the ability of highly cohesive implants to define the shape of the breast and minimize the chances of double-bubble formation has, in the author's experience over the past 18 years, been remarkably consistent. They also have produced exceptionally stable long-term cosmetic results.

Mentor's novel attempt to identify a specific fill percentage appropriate for each style and volume of implant within their MemoryGel Xtra product line, aims to produce the shape stability of a more highly cross-linked gel implant with a softer, more natural feel. Early clinical usage, in this physician's experience, suggests that these implants have an exceptional ability to efficiently store Strain-Energy and define the breast shape while also offering patients a very appealing and natural softness. Furthermore, initial intra and postoperative observations indicate that MemoryGel Xtra's higher degree of gel fill reduces the chance of visible or palpable rippling/wrinkling while producing exceptional projection. While the long-term clinical performance of these implants is yet to be elucidated, this benchtop testing coupled with early clinical experience gives us a first look at the performance characteristics of Mentor MemoryGel Xtra implants and their precision filling. Further testing along with a robust assessment of clinical experience with these devices will be necessary to unequivocally prove this thesis, however.

CLINICAL RELEVANCE OF INNOVATIVE MECHANICAL TESTING TECHNIQUES

Given the detrimental effects that can result from the failing mechanical properties of a breast implant and, specifically, environmental aging of silicone rubber,[13] it is essential that long-term clinical data be periodically compared with the results of the mechanical testing performed in support of PMA approval to determine how accurately these tests predicted the clinical performance of these implants. These comparisons will further document the validity of current testing protocols and elucidate new ways in which testing standards can be updated and refined to more accurately predict the clinical performance of these devices in a variety of clinical settings.

Historically, many of the problems associated with breast implants have not become evident until large numbers of them had been implanted and left in place for many years. The ability to take predictive data derived from bench testing and incorporate them into a meaningful discussion with prospective patients is very appealing to surgeons and patients alike. As more advanced and accurate methods of mechanical testing are developed and adopted as industry standards, the test results will better serve as a surrogate for predicting complex clinical and patient-specific performance characteristics. This will provide both physicians and patients with critical additional information leading to a more informed breast implant selection.

David A. Caplin, MD
Parkcrest Plastic Surgery
845 N. Ballas Court, Suite 300
St. Louis, MO 63141
gfts27@aol.com

ACKNOWLEDGMENTS

The author acknowledges Orchid Garcia and Megan Estes, of Mentor Worldwide, LLC, who provided technical and writing assistance during the development of this article.

REFERENCES

1. Peters W. The evolution of breast implants. *Can J Plast Surg.* 2002;10:223–236.
2. Kinney BM, Jeffers LL, Ratliff GE, et al. Silicone gel breast implants: science and testing. *Plast Reconstr Surg.* 2014;134:47S–56S.
3. Maxwell GP, Gabriel A. The evolution of breast implants. *Plast Reconstr Surg.* 2014;134:12S-7S.

4. O'Shaughnessy K. Evolution and update on current devices for prosthetic breast reconstruction. *Gland Surg*. 2015;4:97–110.
5. Yu LT, Latorre G, Marotta J, et al. *In vitro* measurement of silicone bleed from breast implants. *Plast Reconstr Surg*. 1996;97:756–764.
6. Regulatory history of breast implants in the U.S. 2018; Available at https://www.fda.gov/MedicalDevices/ProductsandMedicalProcedures/ImplantsandProsthetics/BreastImplants/ucm064461.htm. Accessed May 9, 2018.
7. Kessler DA. The basis of the FDA's decision on breast implants. *N Engl J Med*. 1992;326:1713–1715.
8. U.S. Department of Health and Human Services, Food and Drug Administration. *Guidance for Industry and FDA Staff: Saline, Silicone Gel, and Alternative Breast Implants*. Rockville, Md.; 2006. Available at: www.fda.gov/downloads/medicaldevices/deviceregulationandguidance/guidancedocuments/ucm071233.pdf.
9. Cole NM. Consequences of the F.D.A. Directed Moratorium on Silicone Gel Breast Implants - 1992–2006. *Plast Reconstr Surg*. 2018.
10. Ramião NA, Martins PA, Barroso MD, et al. Mechanical performance of poly implant prosthesis (PIP) breast implants: a comparative study. *Aesthetic Plast Surg*. 2017;41:250–264.
11. Greenwald D, Moloye O, Ondrovic L, et al. Mechanical and sensory testing of overfilled breast implants. *Aesthet Surg J*. 2006;26:29–34.
12. Greenwald DP, Randolph M, May JW Jr. Mechanical analysis of explanted silicone breast implants. *Plast Reconstr Surg*. 1996;98:269–272; discussion 273.
13. Wolf CJ, Brandon HJ, Young VL, et al. Chemical, physical and mechanical analysis of explanted breast implants. *Curr Top Microbiol Immunol*. 1996;210:25–37.