Published in final edited form as:

Laryngoscope. 2018 May ; 128(5): 1163–1169. doi:10.1002/lary.26963.

Impact of Medialization Laryngoplasty on Dynamic Nanomechanical Vocal Fold Structure Properties

Gregory R. Dion, MD^{1,3}, Peter A. Benedict, BA¹, Paulo G. Coelho, DDS, PhD², Milan R. Amin, MD¹, and Ryan C. Branski, PhD¹

¹NYU Voice Center, Department of Otolaryngology-Head and Neck Surgery, New York University School of Medicine, New York, NY

²Department of Biomaterials and Biomimetics, New York University College of Dentistry, New York, NY

³Department of Otolaryngology – Head and Neck Surgery, Brooke Army Medical Center, Fort Sam Houston, TX

Abstract

Objectives/Hypothesis—Although the primary goal of medialization laryngoplasty is to improve glottic closure, implant placement is also likely to alter the biomechanical properties of the vocal fold. We sought to employ novel, nano-scale technology to quantify these properties following medialization based on the hypothesis that different medialization materials will likely yield differential biomechanical effects.

Study Design—Ex vivo

Methods—Nine pig larynges were divided into three groups: control, silastic block medialization, or Gore-Tex medialization. Laryngoplasty was performed on excised, intact larynges. The larynges were then bisected in the sagittal plane and each subjected to dynamic nanomechanical analysis (nano-DMA) at nine locations using a 250µm flat-tip punch and frequency sweep load profile across the free edge of the VF and inferiorly along the conus elasticus.

Results—Silastic block and Gore-Tex implant introduced increased storage and loss moduli. Overall, storage moduli mean (max) increased from 38kPa (119) to 72kPa (422) and 129kPa (978) in control, Gore-Tex, and silastic implants. Similarly, loss moduli increased from 13kPa (43) to 22kPa (201) and 31kPa (165), respectively. Moduli values varied widely by location in the silastic block and Gore-Tex groups. At the free vocal fold edge, mean (max) storage moduli were actually lowest in the Gore-Tex group, 20kPa (44), compared to control, 34.5kPa (86), and silastic, 157.9kPa (978), with similar loss and complex moduli trends.

Please address all correspondence to: Ryan C. Branski, PhD, NYU Voice Center, Department of Otolaryngology-Head and Neck Surgery, 345 East 37th Street, Suite 306, New York, NY 10016, Phone: 646.754.1207, Fax: 646.754.1222, ryan.branski@nyumc.org.

The authors have no conflicts of interest or financial disclosures.

Contents of this manuscript were accepted for podium presentation at the American Laryngological Association in April 2017 in Chicago, IL.

Conclusions—Medialization laryngoplasty altered vocal fold structure biomechanical properties; silastic and Gore-Tex implants differentially impact these properties.

Level of Evidence—N/A

Keywords

larynx; vocal fold; mechanical testing; storage moduli; loss moduli; complex moduli; Tan Delta; voice

INTRODUCTION

A range of therapeutic options are available to address glottic insufficiency associated with vocal fold immobility. A recent review identified over 500 studies regarding four primary procedures for vocal fold immobility; however, no differences in outcomes were observed between these rehabilitative techniques.¹ First described by Isshiki, medialization laryngoplasty involves the insertion of an implant into the paraglottic space through a lateral window in the thyroid cartilage at the level of the vocal fold.² Numerous materials have been employed for medialization. No reports exist on how these differing materials affect the dynamic biomechanical properties of the vocal fold (VF).

To date, the majority of laboratory research regarding medialization laryngoplasty has focused on the immunogenic/histologic effects of implants, and the gross static changes in VF length, position, and tension following surgery.^{3–6} Because phonation is a dynamic process dependent on the appropriate production of a mucosal wave propagating from the conus elasticus through the free edge of the true vocal fold, we hypothesize that investigation regarding the viscoelastic VF properties have substantive clinical relevance. Despite intense interest in the varying viscosities of compounds used in injection medialization laryngoplasty, only one review and a single study investigated the effects of implant stiffness on dynamic outcomes following medialization.^{7,8} In that study, Zhang et al investigated the effect of three silicone implants of varying rigidity on acoustic function in excised human VFs.⁸

A number of recent dynamic models have shown promise for the assessment of VF properties including force-elongation measurement, linear skin rheometry, simple-shear parallel plate rheometry, torsional parallel plate rheometry, and indentation.^{9–11} Recently, our group described the utility of a nanoindentation-based method using dynamic nanomechanical analysis (nano-DMA) to precisely explore VF biomechanics on a micrometer scale.^{9,12} Although other indentation techniques have been used to analyze the static, elastic properties of the VFs (specifically Young's modulus), our laboratory described dynamic, viscoelastic biomechanical properties of the excised VFs.^{13,14} Nano-DMA involves the application of a non-destructive force to tissue via a small probe and recording the displacement of the tissue in response to this force. Specifically, nano-DMA allows for quantification of the dynamic elastic characteristics of a material through the storage modulus and the viscous properties of a material through the loss modulus. Nano-DMA has been used previously to analyze a wide range of materials and tissue types.^{15–18} Most recently, our laboratory investigated the properties of the vocal folds via nano-DMA in the

context of an intact, healthy hemilarynx *ex vivo*.⁹ In the current study, we sought to assess the sensitivity of nano-DMA to manipulation of the vocal folds (e.g., medialization) and to quantify the effects of medialization on the biomechanical properties of the vocal folds as a function of the material employed (e.g., silastic block or Gore-Tex strip) for medialization.

METHODS

Tissue Preparation and Setup

Nine flash frozen (-80°C) female pig larynges thawed at -20°C for at least 24 hours were either bisected with a tissue band saw to maintain an intact hemilarynx for testing or thawed at 4°C for 2–4 hours for medialization laryngoplasty. Three specimens underwent Gore-Tex medialization, and three specimens underwent silastic block medialization. To accurately simulate medialization laryngoplasty, both types of medialization (Gore-Tex and silastic block) were performed on intact larynges (Figure 1). Specimens undergoing medialization laryngoplasty were bisected immediately after the medialization and tested. Nanomechanical testing was completed using a previously developed testing apparatus to hold the hemilarynx in place, with testing for each larynx completed during a single sitting.⁹ Specimens were marked at three locations across the free edge of the vocal fold; anterior commissure region, mid-membranous vocal fold, and just anterior to the vocal process. Similar markings were made in the same anterior-posterior position 5mm and 1cm inferiorly.

Gore-Tex Medialization Laryngoplasty

Using three intact, thawed, pig larynges, a $4\text{mm} \times 8\text{mm}$ window was made in the thyroid cartilage 3mm above the lower border of the thyroid cartilage and 5mm posterior to the anterior border of the thyroid cartilage (Figure 1A). While visualizing the larynx from above, a 0.6mm Gore-Tex cardiovascular patch (W.L. Gore, Flagstaff, AZ) was carefully folded horizontally into the window until the ipsilateral true vocal fold (TVF) was at midline (Figure 1B). After medialization, the larynx was sagittally bisected, maintaining an intact anterior commissure on the medialized side and immediately subjected to mechanical testing.

Silastic Block Medialization

Using three intact, thawed, pig larynges, a $4\text{mm} \times 13\text{mm}$ window was made through the thyroid cartilage 3mm above the lower border of the thyroid cartilage. A Silastic block wedge was sculpted to fit within the window, carefully adjusted in each larynx to medialize the vocal fold to midline (Figure 1C). The larynx was then sagittally bisected and subjected to mechanical testing.

Dynamic Nanomechanical Testing

A Hysitron TI950 TriboIndenter® (Minneapolis, MN) was used for nano-mechanical testing equipped with a $250\mu\text{m}$, round, flat-tip punch. The tip was calibrated in both dry and wet environments using Hysitron Triboscan™ software calibration procedures. A variety of load function values and profiles were assessed to ensure adequate tip-tissue contact and the collection of data throughout a variety of frequencies. A $1000\mu\text{N}$ force was applied over a frequency sweep from 10 to 105Hz with a $220\mu\text{N}$ setpoint value. All data were recorded

using the Hysitron Triboscan™ software. An automated pattern collection of four indentations were programmed for each of the nine indentation locations (Figure 2A) designed far enough apart to avoid local tissue changes from indentation.

Data Analysis

Similar to prior nano-indentation work on the intact hemilarynx, nine locations were tested on each specimen at eight different frequencies between 10 and 200Hz (10, 23.6, 37.1, 50.7, 64.3, 77.9, 91.4, and 105Hz) for comparative data.⁹ Average indentation depth at each location was 2,763nm for each cycle. Room temperature saline was applied to the hemilarynx every 20 minutes throughout implantation surgery as well as testing to maintain tissue hydration. Intra- and inter-intervention group data were compared at the nine separate indentation locations. Loss and Storage Moduli are described as a function of intervention type, specimen, frequency, and inferior-superior-anterior-posterior position using scatter plots constructed using R and RStudio (v0.99.879).

Data Presentation

A nine segment grid following the contours of the 9 regions tested by in each specimen was designed. Storage/loss moduli data were then input using the data visualization software Tableau 10.0 (Tableau Software, Seattle, WA) to produce heat maps of laryngeal nano-indentations. These heat maps are visual representations of data in which values were hierarchically color-coded by anatomic subsite to allow for intuitive recognition of areas with high or low storage/loss moduli values.

RESULTS

Sample storage modulus values from repeated indentations at a single point of interest (the midpoint along the true vocal fold margin in Figure 2B) are shown in Figure 3. These data are from one of the control larynges and demonstrated that, although the local indentations (as shown in Figure 2A) were separated by at least 125µm, progressive “stiffening” of the local area was observed on repeated measures. As a result, only initial successful indentation data were used in the remaining analyses. In rare cases that the initial location did not make contact with the tissue specimen under the automated program (resulting in all zero values), data were only analyzed from the first spot where contact was made. Eight locations out of 81 total failed to yield meaningful data related to this confound; in these cases, the second programmed spot was employed, and in one case, data from the fourth programmed spot was collected.

During initial review of the data, it became apparent that for one of the control samples, the tip never fully contacted the specimen in a single region (the furthest posterior horizontal location along the TVF margin) and all resulting values were 0; this location was omitted from the data presentation and analysis.

Each of the nine indentation locations across all nine larynges had corresponding curved storage and loss modulus relationships across the sampled frequencies, similar to Figure 3. The curve shapes and values differed between locations within a sample as well as locations between samples of the same kind of intervention (or control) and across intervention types.

As such, the range, mean, and median kPa values were determined at each point for both the storage and loss modulus to use for comparison and analysis. During each indentation, the nano-indenter tip maintained contact with the surface of the specimen as it cycled through rotations at the eight specified frequency bins. The standard deviations within these individual measurements during indentation varied between 0.01 and 4.42kPa for storage moduli and 0.01 and 5.6kPa for loss moduli.

Figures 4, 5, and 6 display heat maps for each of the larynges tested as well as aggregate data for each intervention (control, silastic block, or gore-tex implant). These maps are divided into nine regions based on each of the nine indentation locations and provide a visual representation of the experimental data. Table 1 and Table 2 include the aggregate range, mean, and median kPa storage and loss modulus data, respectively, calculated among the three specimens as a function of intervention type at each of the nine points sampled.

Globally, storage moduli mean (max) increased from 38kPa (119) to 72kPa (422) and 129kPa (978) in control, Gore-Tex-, and silastic-implanted larynges. Similarly, loss moduli increased from 13kPa (43) to 22kPa (201) and 31kPa (165), respectively. Aggregate storage moduli values (Figure 4B, Table 1) varied widely in the silastic and Gore-Tex groups compared to controls. This finding was particularly pronounced along the row of measurements 5mm below the TVF margin where mean (median) values were 25–39kPa (29–38kPa) compared to 54–269kPa (39–67kPa) in the silastic group and 44–143kPa (40–90kPa) in the Gore-Tex group. In addition, variability was observed in the anterior-most and posterior-most position along the free vocal fold margin in the silastic group, with the aggregate storage modulus values for all specimens within the group ranging from 19–978kPa anteriorly and 5–492kPa posteriorly, compared to 28–86kPa anteriorly and 0–77 posteriorly in the aggregate of the control specimens. At these locations, the data from the Gore-Tex group were closer, although lower in value, comparatively at a range of 9–42kPa anteriorly and 9–42kPa posteriorly.

Aggregate loss modulus values (Figure 4C, Table 2), which increased throughout the frequency bins opposing the behavior of the storage modulus in viscoelastic materials, varied in a similar profile to the storage modulus. Specifically, the aggregate range (median) of the control and Gore-Tex groups varied between 4–23kPa (13kPa) anteriorly and 0–27kPa (5kPa) posteriorly and 0–18kPa (8kPa) anteriorly and 0–26kPa (8kPa) posteriorly, respectively. The silastic group aggregate range (median) varied from 0–144kPa (12kPa) anteriorly and 2–94kPa (8kPa) posteriorly.

The greatest variability occurred in the anterior and poster regions in the silastic and Gore-Tex samples based on analysis of individual specimens (Figure 5 for storage modulus values and Figure 6 for lost modulus values). Heat maps were generated using a color scheme from blue (lower values) to red (high values) corresponding to moduli values, with Figure 4B/C serving as an illustration of the median data column in Table 1 and Table 2. To create a scale as well as lower and upper color limits between blue and red, the overall median storage modulus for the 81 locations (nine locations on nine specimens) was calculated at 81kPa, with a large standard deviation of 141kPa. The scale for these data was set at $\pm$ one standard deviation from the average median value as one standard deviation included zero.

Therefore, any measurement of 222kPa or above was represented as red, and 0 was set to blue. Of note, five values above 222kPa were obtained, of which four occurred in one of the silastic block samples and the other in one of the Gore-Tex samples. The colors on the heat map illustrate the numerical trend of increasing storage modulus extending inferiorly from the free vocal fold edge in all specimens, with this increase highly variable and exaggerated in specimens that underwent silastic block or Gore-Tex medialization. Similarly, heat map representations of the loss modulus in the nine specimens appear almost identical. The overall average of the 81 median loss modulus values was 22kPa, with a standard deviation of 27kPa, so 0 was set as blue, and 1 standard deviation above the aggregate median value 49kPa (22kPa + 27kPa) was set to red. In the resulting heat map illustrating the numerical loss moduli values, values from silastic block and Gore-Tex medialization were widely variable and increased more inferiorly than was seen on the heat map for control specimens.

DISCUSSION

Surgical interventions to address glottic insufficiency have largely failed to account for the effect of medialization on the inherent vocal fold tissue properties. Consideration of these properties can likely further optimize these procedures, in spite of generally favorable outcomes. In that regard, we sought to employ novel technology to provide initial insight into the effects of medialization on the biomechanical properties of the affected vocal folds. Furthermore, we sought to better characterize nano-DMA as a meaningful tool to capture these data. Our preliminary work with nano-DMA was in normal, healthy excised larynges and we sought to query the sensitivity of this technique as a preliminary step for more widespread utility across vocal fold tissue manipulation.

As such, the dynamic storage and loss modulus values from the control group in this study correlated well with the ranges of 6–55kPa for storage moduli and 5–20kPa for loss moduli values at the free vocal fold margin previously reported by our lab using nano-DMA.⁹ These values were, however, higher than some statically collected data from canines and humans, where Young's modulus varied from 2–13kPa in one study and 30–48kPa in another study.^{9,13,19} With regard to medialization, increased storage and loss modulus were seen moving inferior to the free vocal fold margin, particularly anteriorly and posteriorly, with silastic block and, to a lesser extent, Gore-Tex medialization. This finding can likely be explained by the mechanical alterations to the tissue from surgery which resulted in a broad-based implant pushing medially and putting additional strain on the anterior and posterior portions of the vocal fold complex tethered anteriorly to the anterior commissure and posteriorly to the vocal process. Similar to surgical procedures carried out in humans under flexible laryngoscopic visualization, these procedures were performed under direct visualization to optimize medialization. Because implant shape and size varied in the silastic block group and the amount of Gore-Tex folded into the larynx varied in the Gore-Tex group, variations in the resulting mechanical properties are not unexpected.

The wide variability of nano-DMA output was best illustrated in the differences between the aggregate mean and median data found in the silastic and Gore-Tex groups (Table 1). For example, the mean and median storage modulus values of the silastic block group varied from 309kPa and 43kPa anteriorly and 141kPa and 18kPa posteriorly along the free vocal

fold margin and 165kPa and 67kPa anteriorly and 269kPa and 56kPa posteriorly along the data collected 5mm below the free vocal fold margin. Comparatively, the mean and median values were close in all of the aggregate control group locations. In the Gore-Tex aggregate data, variations between the mean and median were most prominent in three regions: posteriorly 5mm below the TVF margin with values of 143kPa and 63kPa, anteriorly 10mm below the free vocal fold edge with values of 116kPa and 70kPa, and in the midpoint with values of 111kPa and 75kPa. These storage modulus data variations can be visualized in Figure 5, where median values are represented for each of the nine sample locations across all specimens, with clear variability evident within the silastic and Gore-Tex groups with both blues and reds in the same test location between specimens as compared to the control group where the colors are similar for the same location between specimens, illustrating the origin of the differences between aggregate mean and median values for the silastic and Gore-Tex groups. With the wide range of data values in Table 1 and Table 2 and the small sample size, the integration of data into heat maps illustrating modulus values at tested locations allowed for visualization of differences between specimens, locations, and intervention types as well as within each of the intervention groups.

Nano-mechanical assessment of tissue properties with silastic block and Gore-Tex implants had limitations. The generated heat maps generalized local tissue properties to a region outside the immediately indented point, which likely was not entirely accurate but provides visualization of measured differences. More clinically, no concomitant phonation was observed during medialization as is the case during sedated surgery in humans; medializations were estimated based solely on adequate medialization of the vocal fold prior to dissection. This limitation may have introduced variability in the size of the implant or quantity of Gore-Tex without confirmation of resulting phonation quality altering both storage and loss modulus values in the medialization groups. Furthermore, permanent tissue deformations prevent testing on the same specimen before and after medialization.

Given the variability found in the implantation groups, larger sample sizes are necessary to make meaningful statistical comparisons between the data collected for the control and medialization groups. In addition, lack of viable data from the automatically programmed, locally spaced nano-indentations at each of the nine locations on each specimen resulted in the inability to collect repeated measures to assess reproducibility within a specimen. Additional determination of the extent of local tissue effects extending from the 250 μ m indentation tip would be useful to determine how close indentations can be to allow for collection of multiple data sets in each region of interest. In spite of these limitations, nano-DMA appears to hold value with regard to the acquisition of geographically precise biomechanical data from the vocal folds.

CONCLUSION

Nano-DMA of the swine hemilarynx after medialization laryngoplasty with both silastic block and Gore-Tex implants demonstrated altered nano-mechanical properties in different regions of the vocal fold complex. These alterations warrant additional investigation to determine how implants may alter phonation not only through glottal shape, but also vocal fold biomechanical properties.

Acknowledgments

Funding for the work described in this manuscript was provided, in part, by the National Institutes of Health/ National Institute on Deafness and Communication Disorders (RO1 DC013277; Principal Investigator-Branski)

References

1. Siu J, Tam S, Fung K. A comparison of outcomes in interventions for unilateral vocal fold paralysis: A systematic review. *The Laryngoscope*. 2016; 126:1616–1624. [PubMed: 26485674]
2. Isshiki N. Progress in laryngeal framework surgery. *Acta oto-laryngologica*. 2000; 120:120–127. [PubMed: 11603755]
3. Noordzij JP, Opperman DA, Perrault DF Jr, Woo P. The biomechanics of the medialization laryngoplasty (thyroplasty type 1) in an ex vivo canine model. *Journal of voice: official journal of the Voice Foundation*. 1998; 12:372–382. [PubMed: 9763188]
4. Noordzij JP, Perrault DF, Woo P. Biomechanics of combined arytenoid adduction and medialization laryngoplasty in an ex vivo canine model. *Otolaryngology--head and neck surgery: official journal of American Academy of Otolaryngology-Head and Neck Surgery*. 1998; 119:634–642. [PubMed: 9852539]
5. Dufresne AM, Lafreniere D. Soft tissue response in the rabbit larynx following implantation of LactoSorb (PLA/PGA copolymer) prosthesis for medialization laryngoplasty. *Journal of voice: official journal of the Voice Foundation*. 2000; 14:387–397. [PubMed: 11021506]
6. Ustundag E, Boyaci Z, Keskin G, Kaur A, Ozkarakas H. Soft tissue response of the larynx to silicone, Gore-Tex, and irradiated cartilage implants. *The Laryngoscope*. 2005; 115:1009–1014. [PubMed: 15933511]
7. Lisi C, Hawkshaw MJ, Sataloff RT. Viscosity of materials for laryngeal injection: a review of current knowledge and clinical implications. *Journal of voice: official journal of the Voice Foundation*. 2013; 27:119–123. [PubMed: 23183372]
8. Zhang Z, Chhetri DK, Bergeron JL. Effects of implant stiffness, shape, and medialization depth on the acoustic outcomes of medialization laryngoplasty. *Journal of voice: official journal of the Voice Foundation*. 2015; 29:230–235. [PubMed: 25499519]
9. Dion GR, Coelho PG, Teng S, Janal MN, Amin MR, Branski RC. Dynamic nanomechanical analysis of the vocal fold structure in excised larynges. *Laryngoscope*. 2016
10. Dion GR, Jeswani S, Roof S, et al. Functional assessment of the ex vivo vocal folds through biomechanical testing: A review. *Materials science & engineering C, Materials for biological applications*. 2016; 64:444–453. [PubMed: 27127075]
11. Chhetri DK, Berke GS, Lotfizadeh A, Goodyer E. Control of vocal fold cover stiffness by laryngeal muscles: a preliminary study. *The Laryngoscope*. 2009; 119:222–227. [PubMed: 19117308]
12. Coelho PG, Sobieraj M, Tovar N, et al. Preliminary investigation of a novel technique for the quantification of the ex vivo biomechanical properties of the vocal folds. *Materials science & engineering C, Materials for biological applications*. 2014; 45:333–336. [PubMed: 25491836]
13. Chhetri DK, Zhang Z, Neubauer J. Measurement of Young's modulus of vocal folds by indentation. *Journal of voice: official journal of the Voice Foundation*. 2011; 25:1–7. [PubMed: 20171829]
14. Chhetri DK, Rafizadeh S. Young's modulus of canine vocal fold cover layers. *J Voice*. 2014; 28:406–410. [PubMed: 24491497]
15. Nayar VT, Weiland JD, Hodge AM. Macrocompression and nanoindentation of soft viscoelastic biological materials. *Tissue engineering Part C, Methods*. 2012; 18:968–975. [PubMed: 22656195]
16. Nayar VT, Weiland JD, Nelson CS, Hodge AM. Elastic and viscoelastic characterization of agar. *Journal of the mechanical behavior of biomedical materials*. 2012; 7:60–68. [PubMed: 22340685]
17. Akhtar R, Schwarzer N, Sherratt MJ, et al. Nanoindentation of histological specimens: Mapping the elastic properties of soft tissues. *Journal of materials research*. 2009; 24:638–646. [PubMed: 20396607]

18. Ebenstein DM, Pruitt LA. Nanoindentation of soft hydrated materials for application to vascular tissues. *Journal of biomedical materials research Part A*. 2004; 69:222–232. [PubMed: 15057995]
19. Oren L, Dembinski D, Gutmark E, Khosla S. Characterization of the vocal fold vertical stiffness in a canine model. *J Voice*. 2014; 28:297–304. [PubMed: 24495431]

Author Manuscript

Author Manuscript

Author Manuscript

Author Manuscript

Figure 1.

Depiction of porcine larynges undergoing medialization laryngoplasty. Regardless of material, a window was made in the thyroid cartilage 3mm above the lower border of the thyroid cartilage (A). Two types of medialization were performed on intact larynges: Gore-Tex (B) and silastic block (C). Following medialization, the specimens were bisected.

Figure 2.

The sequence (numerals 1–4) of four indentations made by the 250 μm diameter, round punch of the Hysitron TI950 TriboIndenter® at each of the nine indentation locations (A). Image of a sectioned hemi-larynx with the testing locations marked with black ink between the anterior commissure (thin arrow) and vocal process (arrow head; B).

Figure 3.

Storage modulus data from repeated indentations at a single point (specifically the midpoint along the true vocal fold margin) plotted as storage modulus (kPa) vs frequency (Hz). Note increased storage modulus values at every frequency with each subsequent trial, indicating progressive stiffening of the local area.

Figure 4.

Hemi-larynx markings employed to create heat map grids (A). Heat maps of aggregate median storage modulus data for control/silastic block/Gore-Tex specimens (B). The mean storage modulus value (of the sample medians) was 46.51 with a standard deviation of 23.88; the color scale minimum and maximum were balanced to two standard deviations from the mean to prevent outliers from skewing the scale. Heat maps displaying the aggregate median loss modulus data for control/silastic block/Gore-Tex specimens (C). The mean loss modulus value (of the sample medians) was 15.96 with a standard deviation of 7.54; the color scale minimum and maximum were balanced to two standard deviations from the mean.

Figure 5.

Individual heat maps of median storage modulus data for every specimen. The mean storage modulus of the sample medians was 80.61 with a standard deviation of 140.68; the color scale minimum and maximum were balanced to one standard deviation from the mean to include zero, but avoid skew relating to outlying data points.

Figure 6.

Individual heat maps of median loss modulus data for every specimen. The mean loss modulus value of the sample medians was 22.16 with a standard deviation of 26.90; the color scale minimum and maximum were balanced to one standard deviation from the mean to include zero, but avoid skew relating to outlying data points.

Summary of the aggregate range, mean and median storage modulus values calculated between all three specimens receiving a given intervention (control/silastic/Gore-Tex). The table is arranged spatially according to the anatomic position of each sampled point.

Table 1

	Horizontal Pos 1			Horizontal Pos 2			Horizontal Pos 3		
	Range	Mean	Median	Range	Mean	Median	Range	Mean	Median
Control	28–86	55	55	3–47	22	20	0–77	27	10
Silastic	19–978	309	43	7–48	23	23	5–492	141	18
Goretex	9–42	26	23	0–44	10	9	9–42	24	24
Control	0–119	39	34	0–50	25	29	0–73	34	38
Silastic	38–588	175	67	23–105	54	39	0–841	269	56
Goretex	22–142	80	90	0–96	44	40	0–422	143	63
Control	26–99	65	66	8–62	41	43	7–67	41	46
Silastic	2–82	47	49	58–138	90	87	29–110	54	46
Goretex	34–247	116	70	55–213	111	75	12–173	93	93

Summary of the aggregate range, mean and median loss modulus values calculated for all specimens receiving each intervention (control/silastic/Gore-Tex). Values are organized spatially according to the anatomic position of each sampled point.

Table 2

	Horizontal Pos 1			Horizontal Pos 2			Horizontal Pos 3		
	Range	Mean	Median	Range	Mean	Median	Range	Mean	Median
Control	4-23	13	13	0-19	5	6	0-27	7	5
Silastic	0-144	49	12	0-15	7	7	2-94	31	8
Goretex	0-18	7	8	0-22	5	4	0-26	9	8
Control	0-32	15	14	0-21	12	14	0-43	17	15
Silastic	9-131	47	21	2-31	16	16	1-165	53	21
Goretex	5-54	22	19	3-32	16	16	3-201	54	20
Control	4-30	18	19	7-24	17	18	7-33	18	18
Silastic	6-34	17	15	16-54	33	34	3-45	23	21
Goretex	8-43	24	21	13-47	28	28	4-48	29	30