Mechanical Characterization Testing for Creating an In-Vitro Vessel Model with Properties and Anatomical Structure Similar to Human Neurovascular

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ATi
Aneuvas Technologies, Incorporated

BDL
Bioengineering Devices Laboratory

Introduction & Importance

Statistical importance:

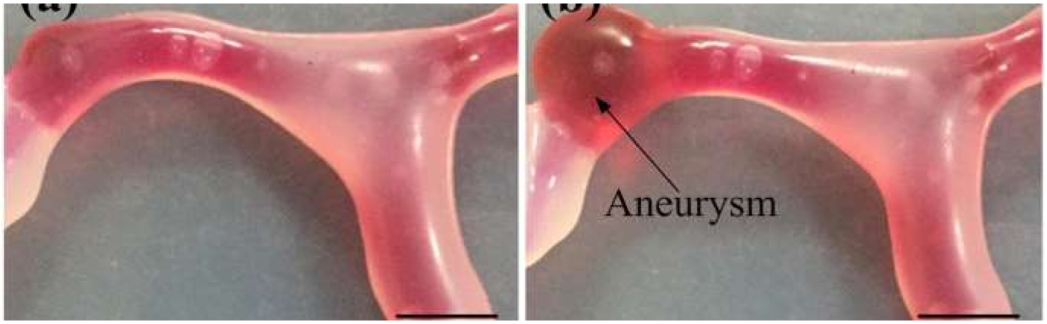
- Estimated 6.5 million people in U.S. have an unruptured aneurysm, or 1 in 50 people.
- 500,000 deaths worldwide per year. Half of the victims are younger than 50.

Model importance:

- Creating a more property accurate model of brain vessels can assist:
  - Medical students
  - Neurosurgeons
  - Bio-Engineers
  - Researchers

Allows for neurosurgeons to practice before preforming the operation which leads to:

- More clear direction of the veins.
- Less mistakes during surgery.
- Increases the safety of the patient.
- Cheaper costs for the patient.



Design Requirements

1. Develop, justify, and characterize the following attributes (recommended but not limited to):

- Virtual design of vessel model using innovative biomaterials
- 3D-print of virtual design for measuring:
- Biaxial vascular tension of materials
- Blood vessel compliance
- Lubricity of model interior
- Compressive and Shear Modulus
- Compatibility with an *in vitro* pressure (and flow) measurement system

2. Allow visualization of device deployment

Design Requirements

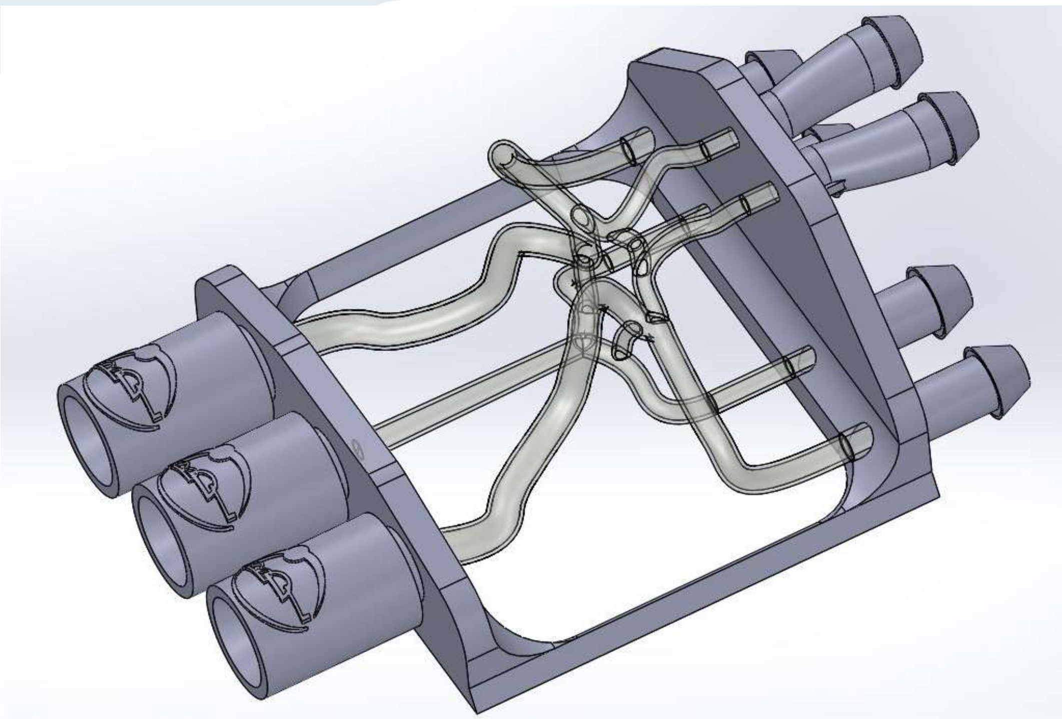
Customer Requirements

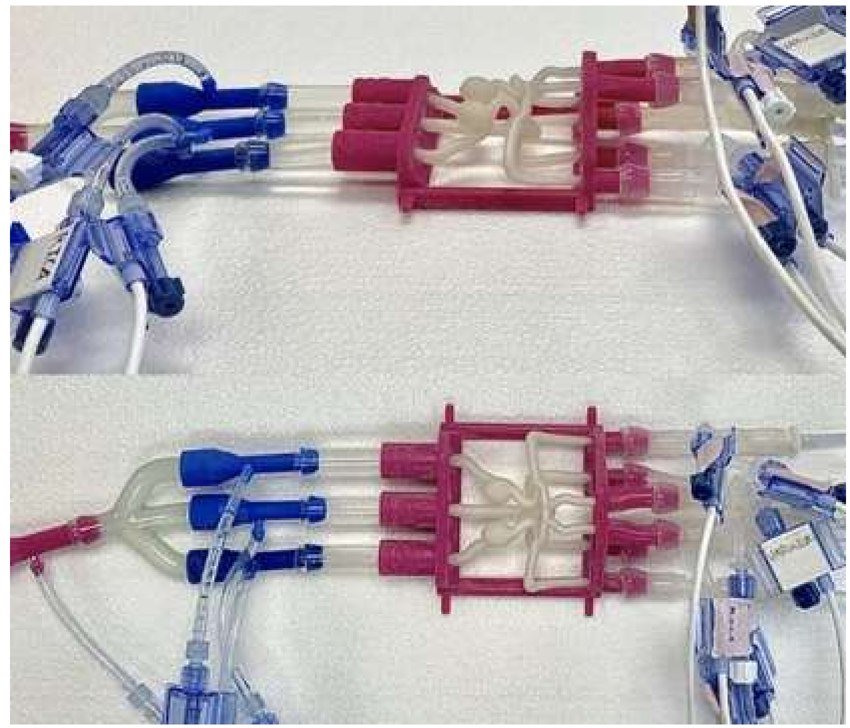
- Size (CR-1)
- Easy to Connect (CR-2)
- Soft Exterior/Hard Interior (CR-3)
- Lightweight (CR-4)
- Material Selection (CR-5)
- Retains Shape (CR-6)
- Similar Properties to Organic Tissue (CR-7)
- Cost Within Budget (CR-8)

Engineering Requirements

- Stiffness (ER-1)
- Thickness (ER-2)
- Compressive Modulus (ER-3)
- Frequency (ER-4)
- Poisson's Ratio (ER-5)
- Compliance (ER-6)
- Angular Acceleration (ER-7)
- Radial Force (ER-8)
- Layering (ER-9)
- Pressure (ER-10)
- Shear Modulus (ER-11)
- Hardness (ER-12)
- Strain (ER-13)
- Coefficient of Friction (ER-14)

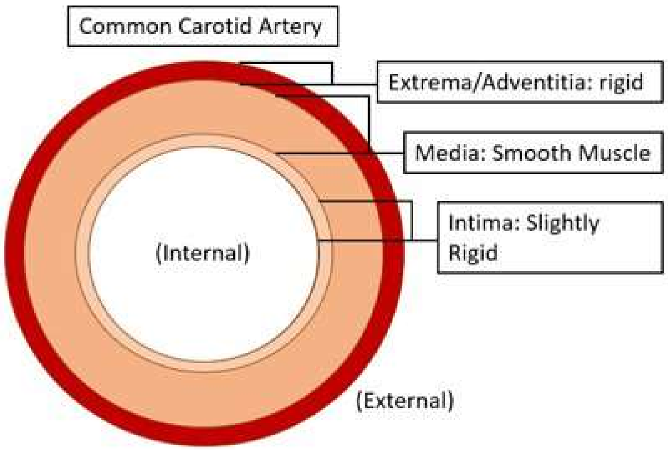
Previous Design



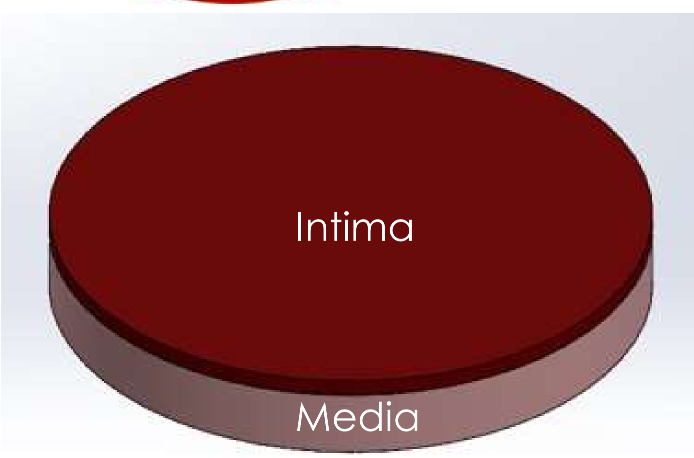


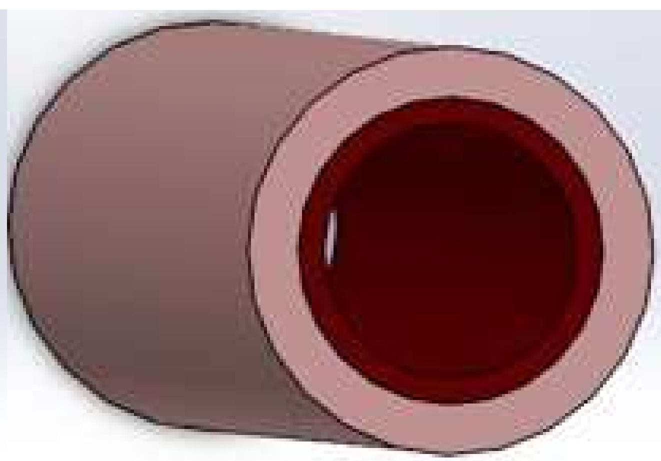
- Single layer model, 1mm thickness overall – exception in the LCA and RCA being 1.2mm thick.
- Aneurysm sacs added to basilar bifurcation, Anterior Communicating, and Internal Carotid segments.

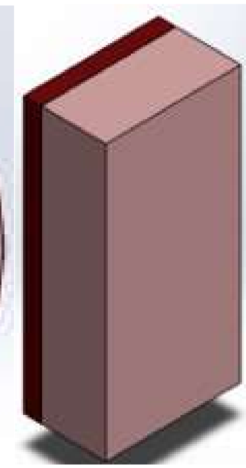
Proposed Sample Design



- Replicate vascular layering.
- Exclude adventitia layer for consistency.
- Redesign 3D CAD with 2 layer vascular.
- Media layer making up 80% of layer; intima making up 20% of layer'
- Media as a softer shore, intima as a more rigid shore hardness.
- Combination of ratios:
  - 30 - 50 (media - intima)
  - 40 - 60 (media - intima)





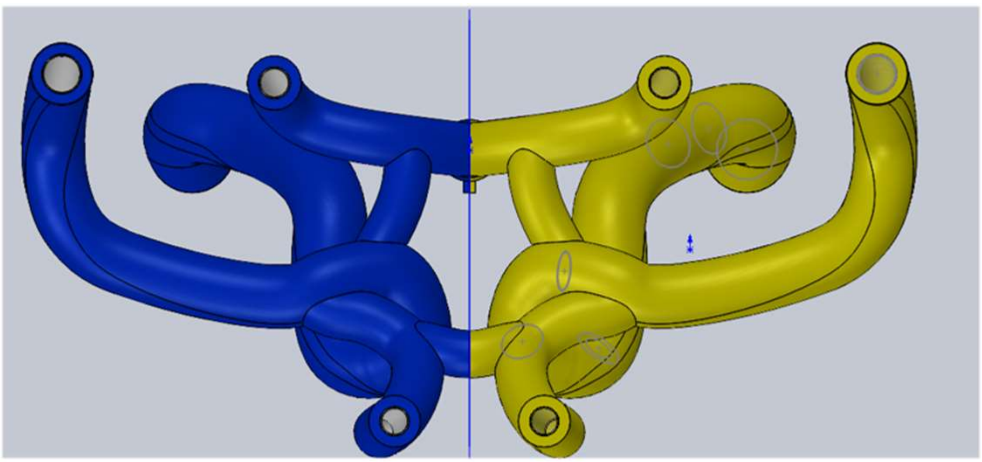


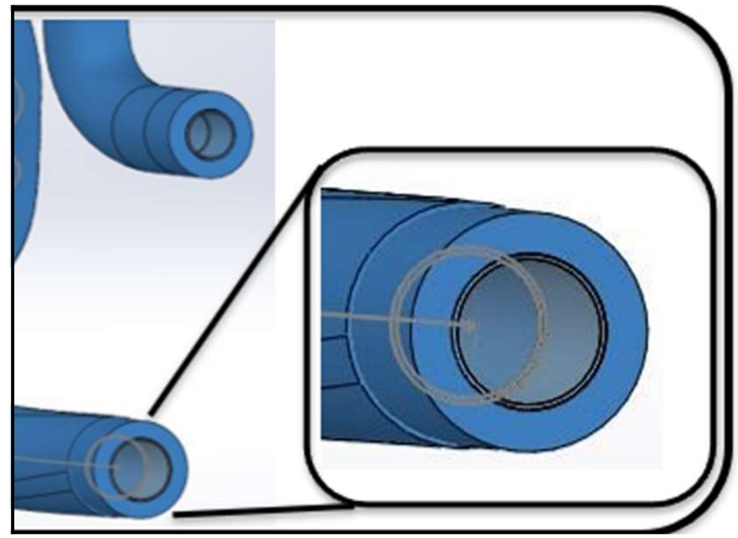
Sample Design

- 1.2mm samples
- Intima: 0.24mm
- Media: 0.96mm

*For above images color key: Intima: Red, Media: Dark Pink

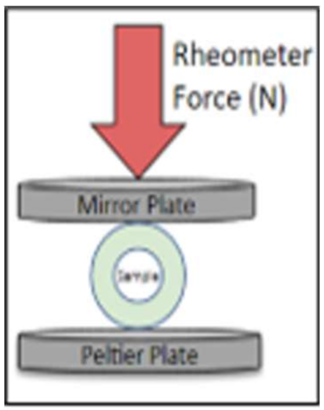
Updated Design (CAD)



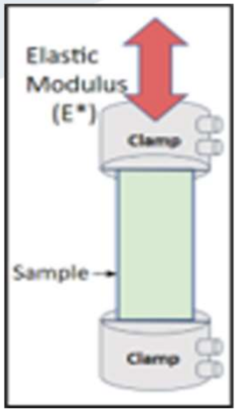


- Same base design for maintained flow model integration.
- Adjusted a 20%-80% layering to 1mm thick CAD.
  - 0.8mm media, 0.2mm intima.
- RCA/LCA:
  - 1mm media, 0.2mm intima at base, thins to 0.8mm media.
- No aneurysm sacs added to this Circle of Willis model.

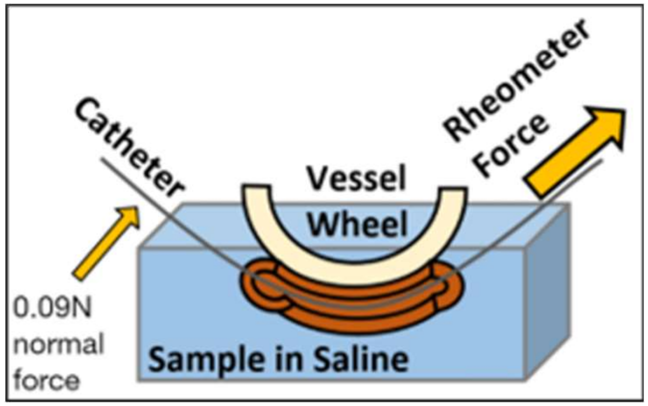
Testing Overview



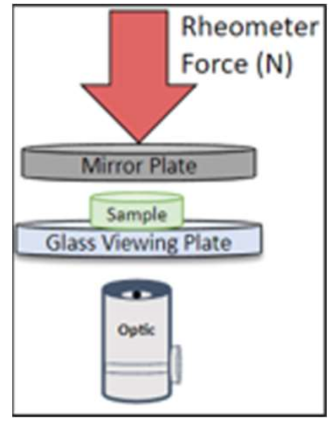
Radial Force



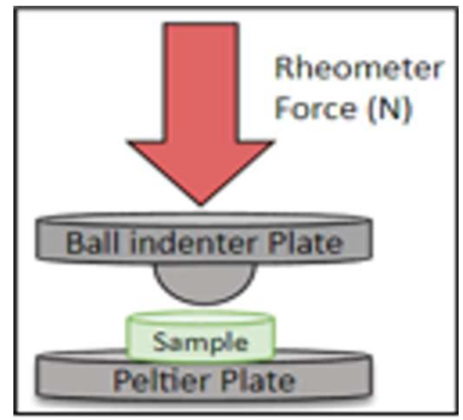
Tension



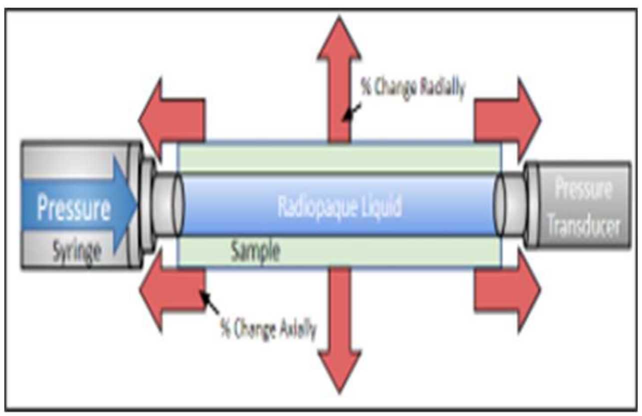
Lubricity



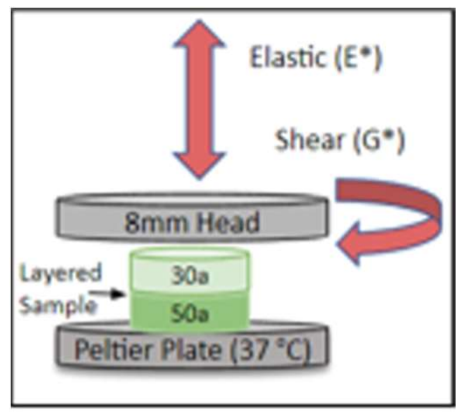
Poisson's Ratio



Hardness

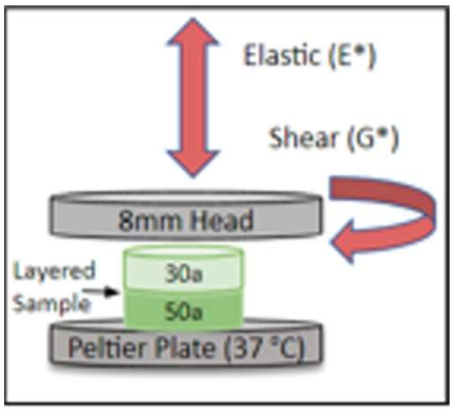


Compliance



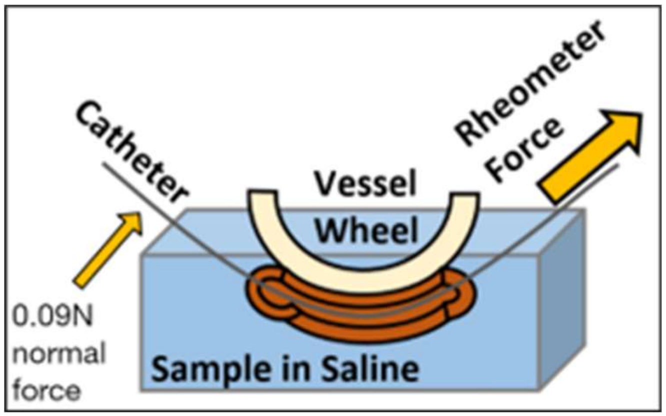
Compression/Shear

Compression and Shear Test



- Procedures
  - Compression: An axial force of 0.9-1.4 N onto a puck sample, measuring how resistant the sample is to the force
  - Shear: A continuous oscillating force, or direct shear, will be applied to a puck sample.
- Reasons for Test
  - Compression: Measures the elastic modulus
  - Shear: Measures the shear modulus

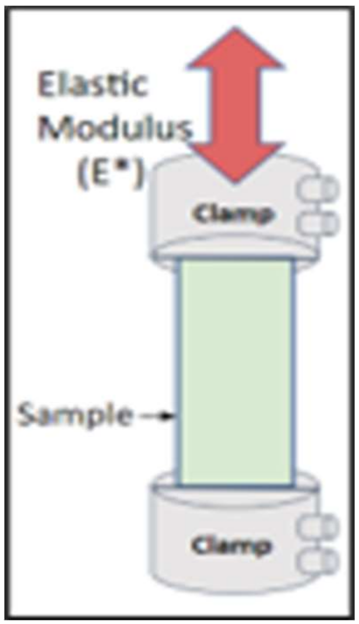
Lubricity Test



- Procedure
  - A tube-shaped sample is secured to the wheel and surgical wire is connected to the rheometer, through the sample , and connected to a syringe. The wire will slowly be pulled through the sample

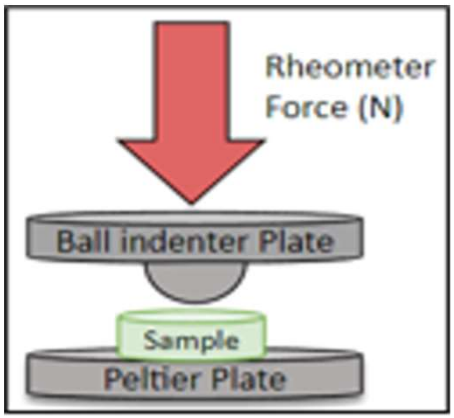
- Reason for test
  - Measures the friction coefficient of the inside of the sample

Tension Test



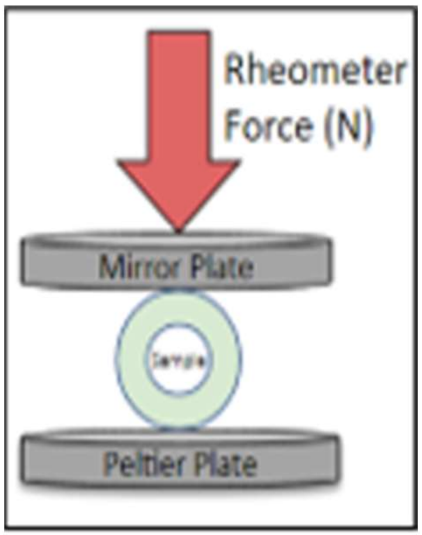
- Procedure
  - A rectangular sample is secured in the rheometer and pulled until it experiences an axial force of 100mHg and then again until it experiences an axial force of 160mmHg
- Reasons for test
  - Measures the tension properties

Hardness Test



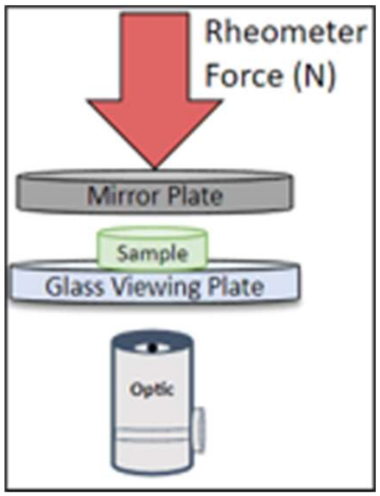
- Procedure
  - A metal ball is compressed into a puck sample at a given rate. The release of energy as the sample is destroyed
- Reason for test
  - Measures the compressive modulus and strain percentage

Radial Force Test



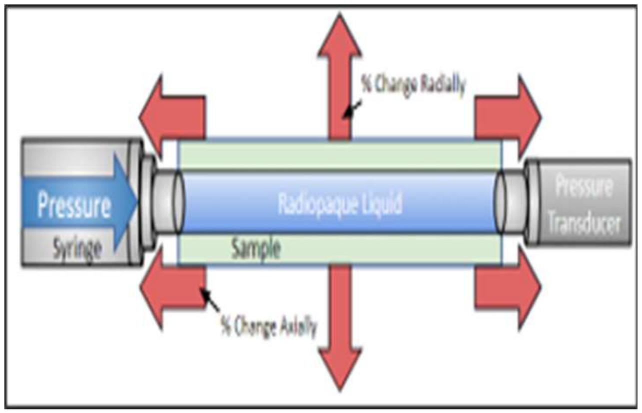
- Procedure
  - A tube sample is compressed to 50% of the total exterior diameter of the sample
- Reason for test
  - Measures the radial force

Poisson's Ratio Test



- Procedure
  - A puck sample is compressed with a known force over a known period. Axial displacement is measured by the calibrated DinoCapture program
- Reason for test
  - Measures the Poisson's ratio

Compliance Test

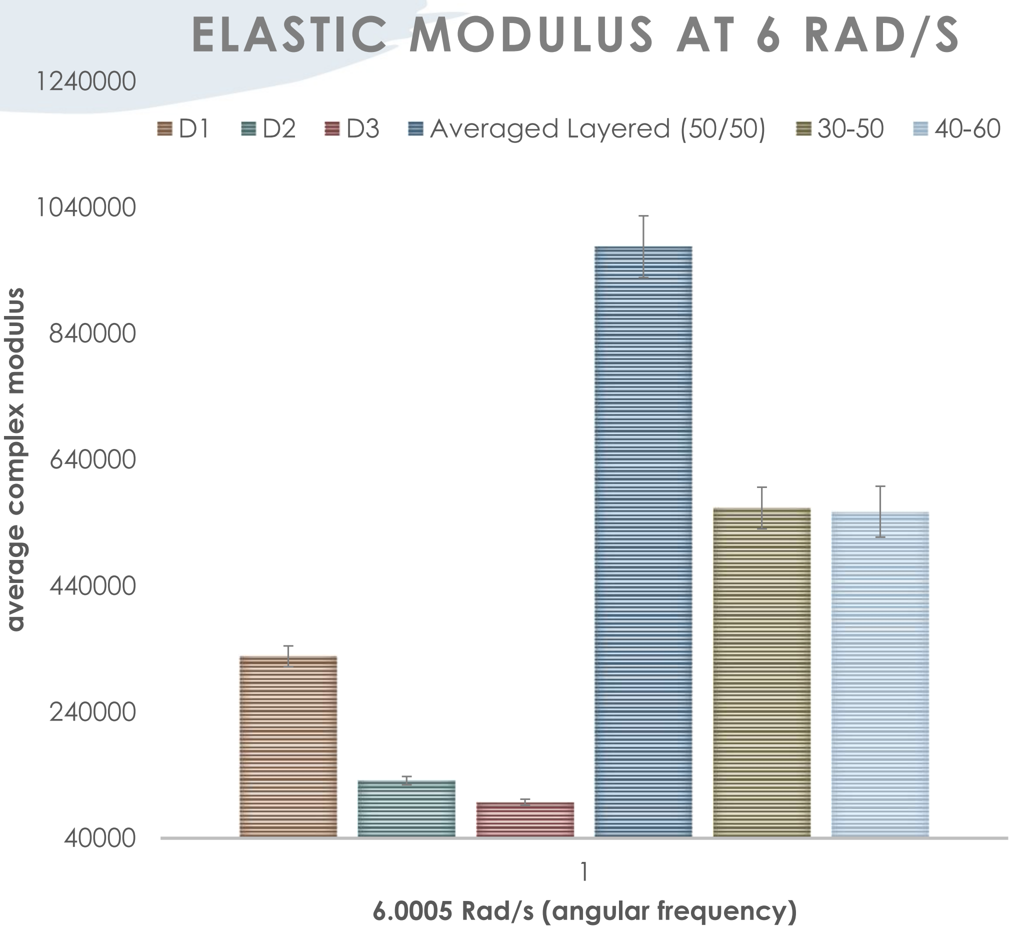


- Procedure
  - A tube sample is filled with liquid until the pressure gauge reads a chosen. The pressure increases in increments and a photo of the sample are taken at every step
- Reason for test
  - Measures the compliance and amount of internal pressure the sample can handle

Detailed Testing Plan: Summary

Experiment/Test	Relevant DRs
T1 - Shear	CR-5, CR-6, CR-7, ER-4, ER-7, ER-11
T2 - Compression	CR-5, CR-6, CR-7, ER-2, ER-3, ER-4, ER-7
T3 - Hardness	CR-5, CR-6, CR-7, ER-12
T4 - Poisson's	CR-5, CR-6, CR-7, ER-4, ER-5, ER-7
T5 - Radial Force	CR-5, CR-6, CR-7, ER-4, ER-7, ER-8
T6 - Tension	CR-5, CR-6, ER-2, CR-7, ER-1, ER-4, ER-7
T7 - Compliance	CR-5, CR-6, CR-7, ER-2, ER-6, ER-10
T8 - Lubricity	CR-5, CR-6, CR-7, ER-7, ER-14

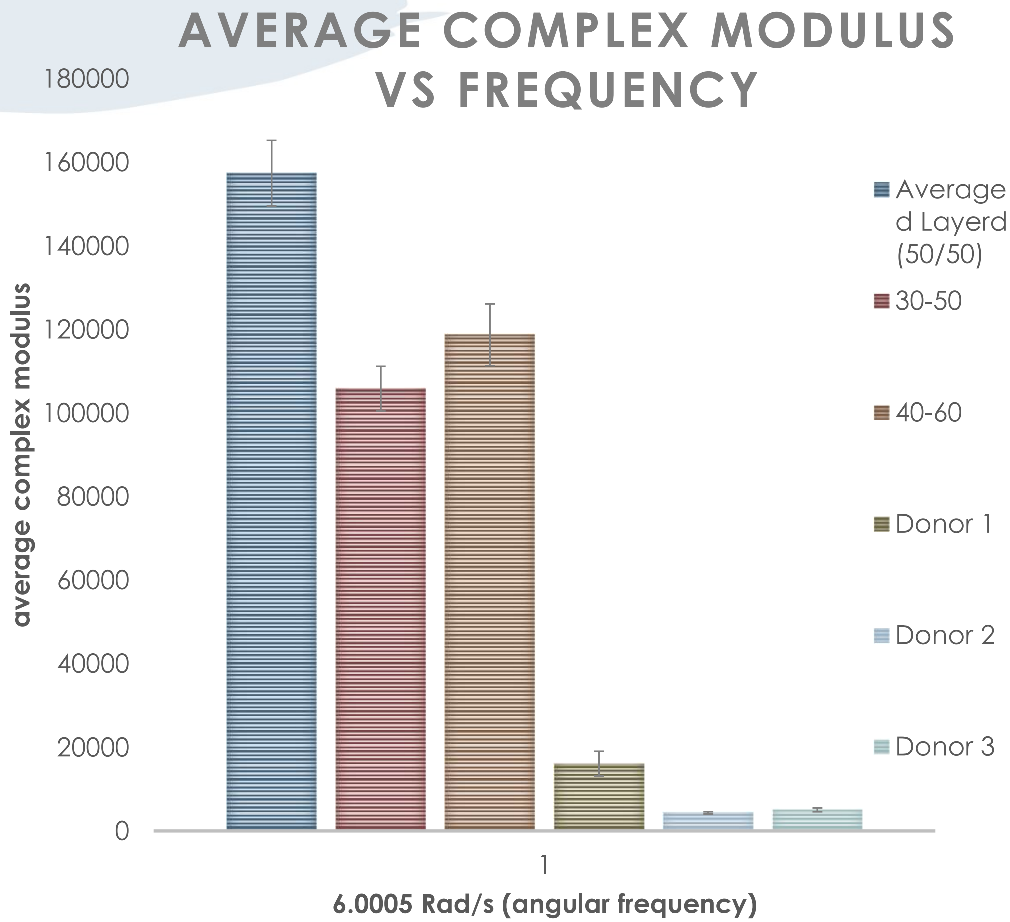
Testing Results: Compression



4 Day Soak								
	30-50		40-60		50% Layered		Silicone	
	% diff.	p value	% diff.	p value	% diff.	p value	% diff.	p value
Compressive moduli								
Donor 1	-22.30	<0.001	-23.59	<0.001	*-22.5*	*< 0.001*	53.7	< 0.001
Donor 2	-76.71	<0.001	-77.10	<0.001	-336	< 0.001	-64.6	< 0.001
Donor 3	-82.82	<0.001	-83.10	<0.001	-310	< 0.001	-54.9	0.005
Avg	-60.60	<0.001	-61.26	<0.001	-222.83	< 0.001	-21.93	0.005

Polymer is less compressive than donors.

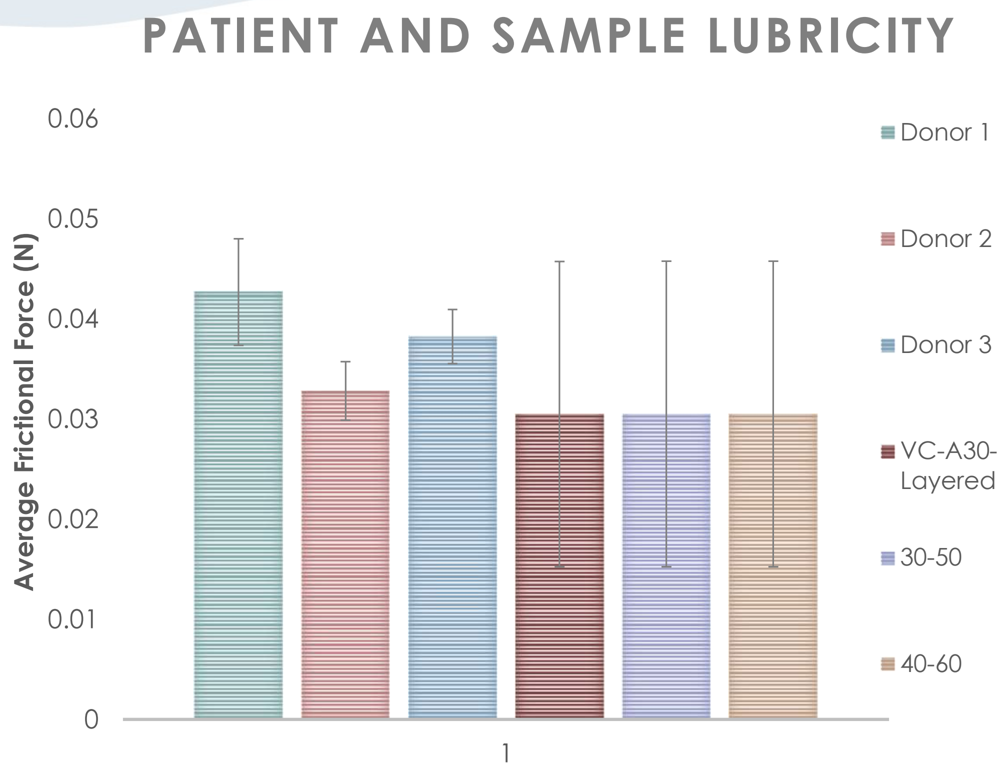
Testing Results: Shear Modulus



4 Day Soak								
	30-50		40-60		50% Layered		Silicone	
	% diff.	p value	% diff.	p value	% diff.	p value	% diff.	p value
Shear moduli								
Donor 1	555.65	<0.001	635.62	<0.001	-823	< 0.001	-387	< 0.001
Donor 2	2330.02	<0.001	2626.36	<0.001	-2850	< 0.001	-1450	< 0.001
Donor 3	1990.33	<0.001	2245.25	<0.001	-1650	< 0.001	-823	< 0.001
Avg	1625.33	<0.001	1835.75	<0.001	-1774.33	< 0.001	-886.66	< 0.001

Polymer displays mixed results in shear resistance.

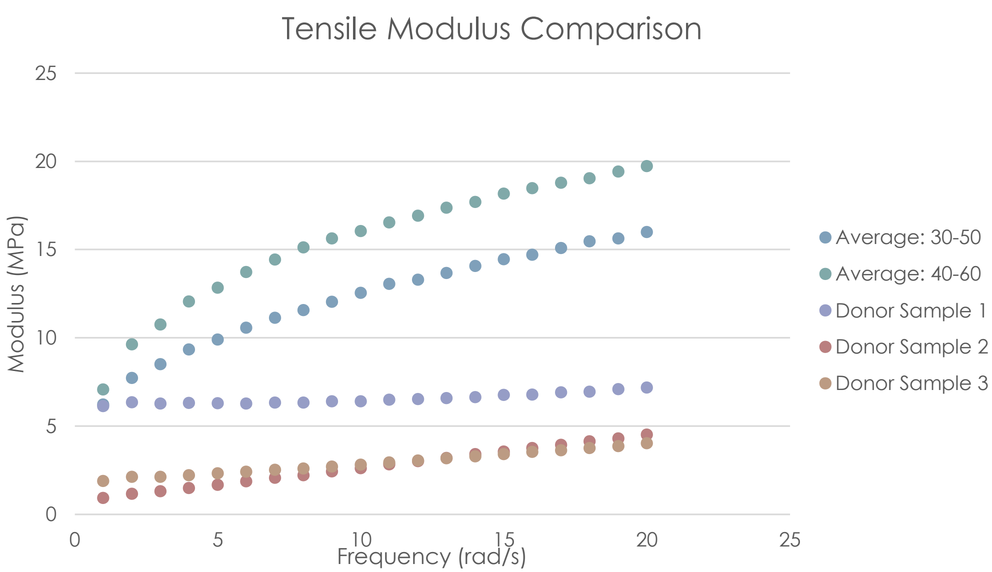
Testing Results: Lubricity



4 Day Soak								
	30-50		40-60		50% Layered		Silicone	
	% diff.	p value	% diff.	p value	% diff.	p value	% diff.	p value
Lubricity								
Donor 1	27.33	<0.001	27.39	<0.001	26.2	< 0.001	64.5	< 0.001
Donor 2	33.39	<0.001	33.45	<0.001	3.93	< 0.001	53.8	< 0.001
Donor 3	31.33	<0.001	31.39	<0.001	17.6	< 0.001	60.4	< 0.001
Avg	30.68	<0.001	30.74	<0.001	15.91	< 0.001	59.56	< 0.001

Polymer is less lubricious than donors.

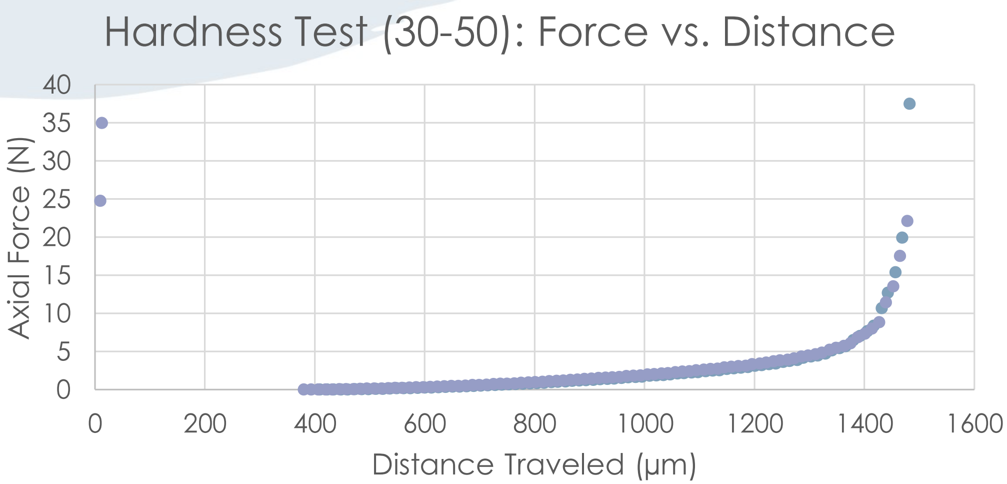
Testing Results: Tensile Modulus

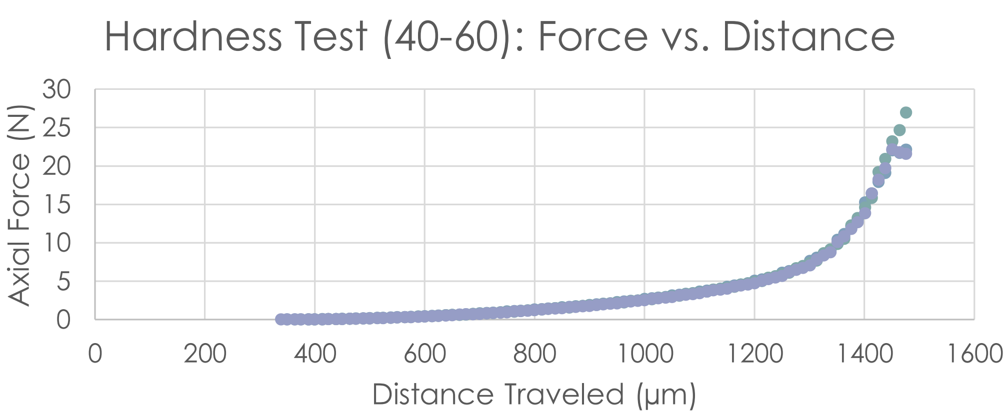


4 Day Soak								
	30-50		40-60		50% Layered		Silicone	
	% diff.	p value	% diff.	p value	% diff.	p value	% diff.	p value
Tensile Moduli at 160mmHg								
Donor 1	10.01	<0.001	13.85	<0.001	-47.4	< 0.001	-97.6	< 0.001
Donor 2	322.15	<0.001	336.87	<0.001	-418	< 0.001	-595	< 0.001
Donor 3	170.04	<0.001	179.45	<0.001	-266	< 0.001	-391	< 0.001
Avg	167.4	<0.001	176.7	<0.001	-243.8	< 0.001	-361.2	< 0.001

Polymer is more resistant to tension.

Testing Results: Hardness

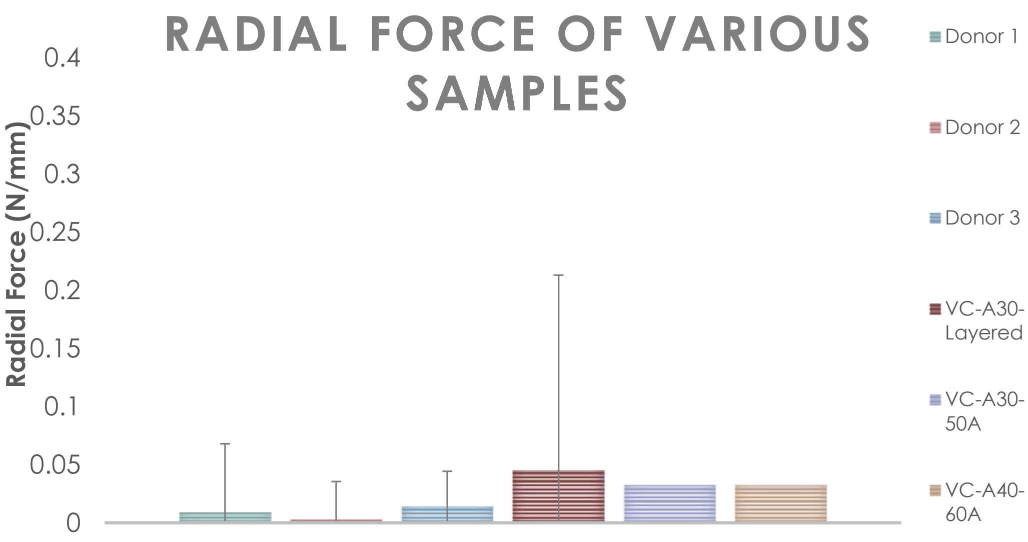




4 Day Soak								
	30-50		40-60		50% Layered		Silicone	
	% diff.	p value	% diff.	p value	% diff.	p value	% diff.	p value
Hardness Moduli								
Donor 1	-99.455	<0.001	289.5	0.58538	2.44	0.796	-77.1	< 0.001
Donor 2	-98.994	<0.001	260.51	0.00013	-100	0.002	-52.9	0.004
Donor 3	-99.155	<0.001	649.55	0.00117	-112	0.009	-50.1	0.048
Avg	-99.202	<0.001	399.55	0.1956	-69.853	0.269	-60.033	0.026

Polymer is softer than donor samples.

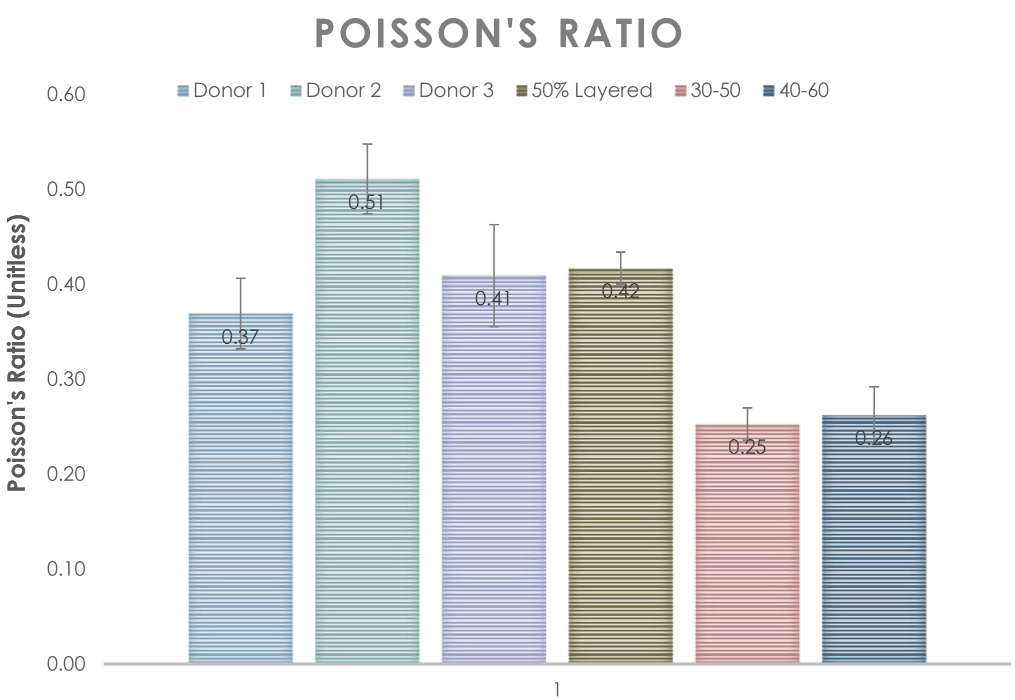
Testing Results: Radial Force



4 Day Soak								
	30-50		40-60		50% Layered		Silicone	
	% diff.	p value	% diff.	p value	% diff.	p value	% diff.	p value
Radial force								
Donor 1	473.45	<0.001	383.04	<0.001	-318	0.001	-5570	0.003
Donor 2	1301.5	<0.001	1080.54	<0.001	-11500	< 0.001	-157000	< 0.001
Donor 3	269.03	<0.001	210.85	<0.001	-169	0.02	-3550	0.003
Avg	681.33	<0.001	558.15	<0.001	-3995.7	0.0105	-55373	0.003

Polymer is more resistant to radial deformation.

Testing Results: Poisson's Ratio

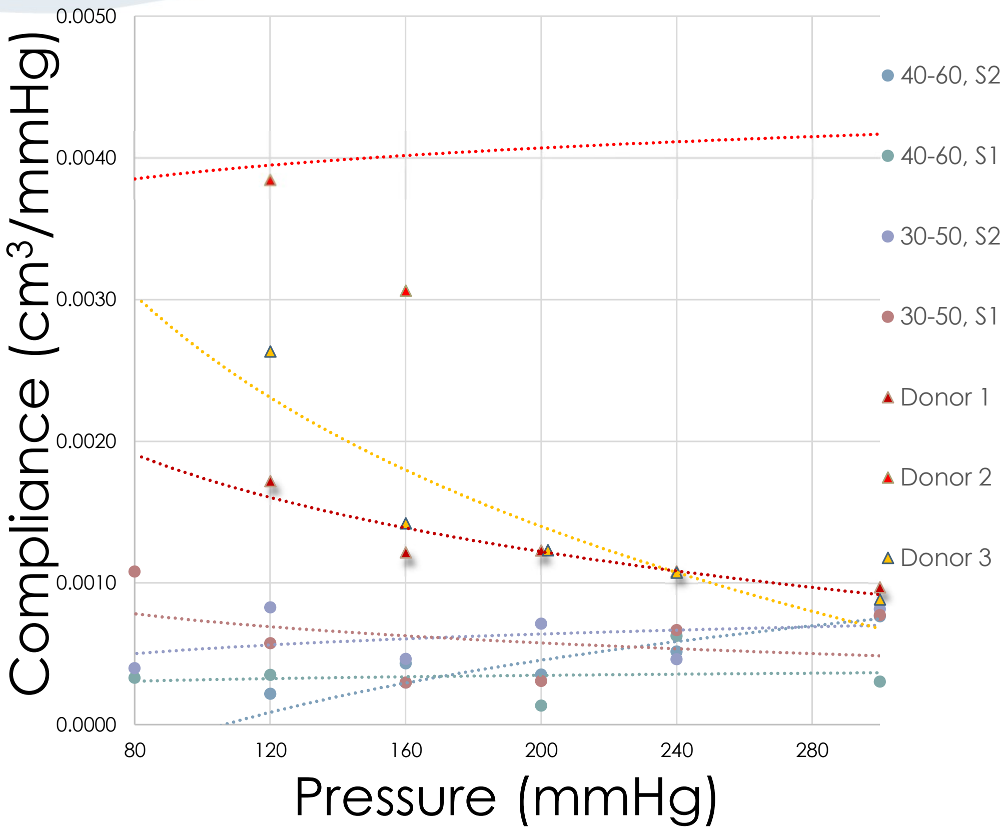


4 Day Soak								
	30-50		40-60		50% Layered		Silicone	
	% diff.	p value	% diff.	p value	% diff.	p value	% diff.	p value
Poisson's Ratio								
Donor 1	-31.51	0.016712	-28.88	0.02464	-15.6	0.356	3.96	0.828
Donor 2	-50.52	<0.001	-48.62	<0.001	16.5	0.128	30.6	0.015
Donor 3	-38.21	0.001303	-35.84	0.002055	-4.32	0.774	13.4	0.391
Avg	-40.08	0.009007	-37.78	0.013351	-1.14	0.419	15.99	0.411

Polymer resists axial deformation less than donors.

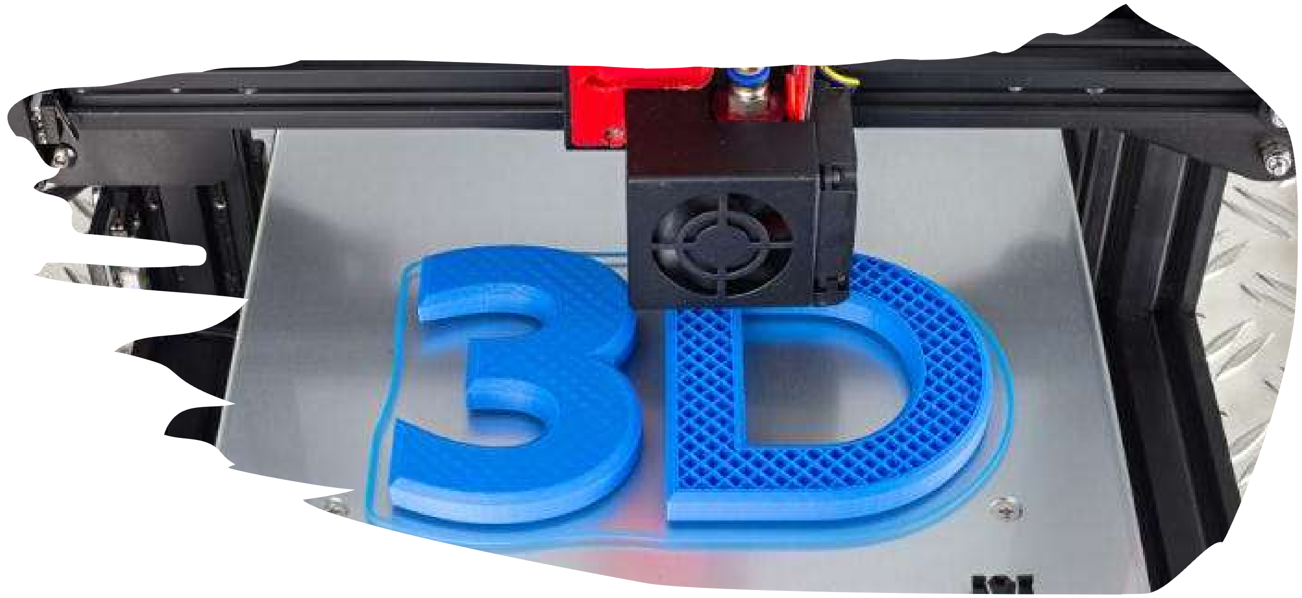
Compliance

Cumulative Compliance



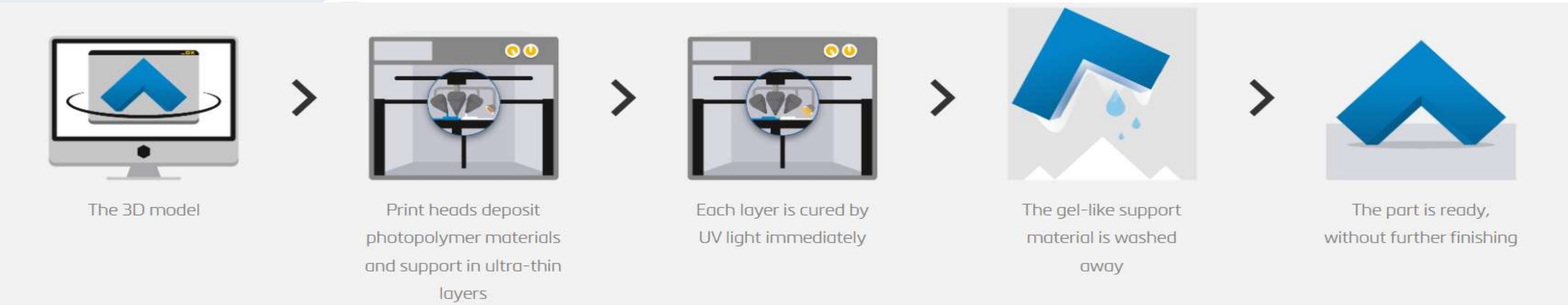
4 Day Soak								
	30-50		40-60		50% Layered		Silicone	
	% diff.	p value	% diff.	p value	% diff.	p value	% diff.	p value
Compliance								
Donor 1	-55.76	<0.001	-70.03	<0.001	-202	< 0.001	*38.4*	*0.249*
Donor 2	-90.18	<0.001	-93.35	<0.001	*27.3*	*0.07*	85.2	< 0.001
Donor 3	-70.32	<0.001	-79.89	<0.001	-102	0.002	58.7	0.041
Avg	-72.08	<0.001	-81.09	<0.001	-92.233	0.036	60.767	0.145

Polymer is less compliant than donors.



Manufacturing of In-Vitro Model

3D Printing of Model



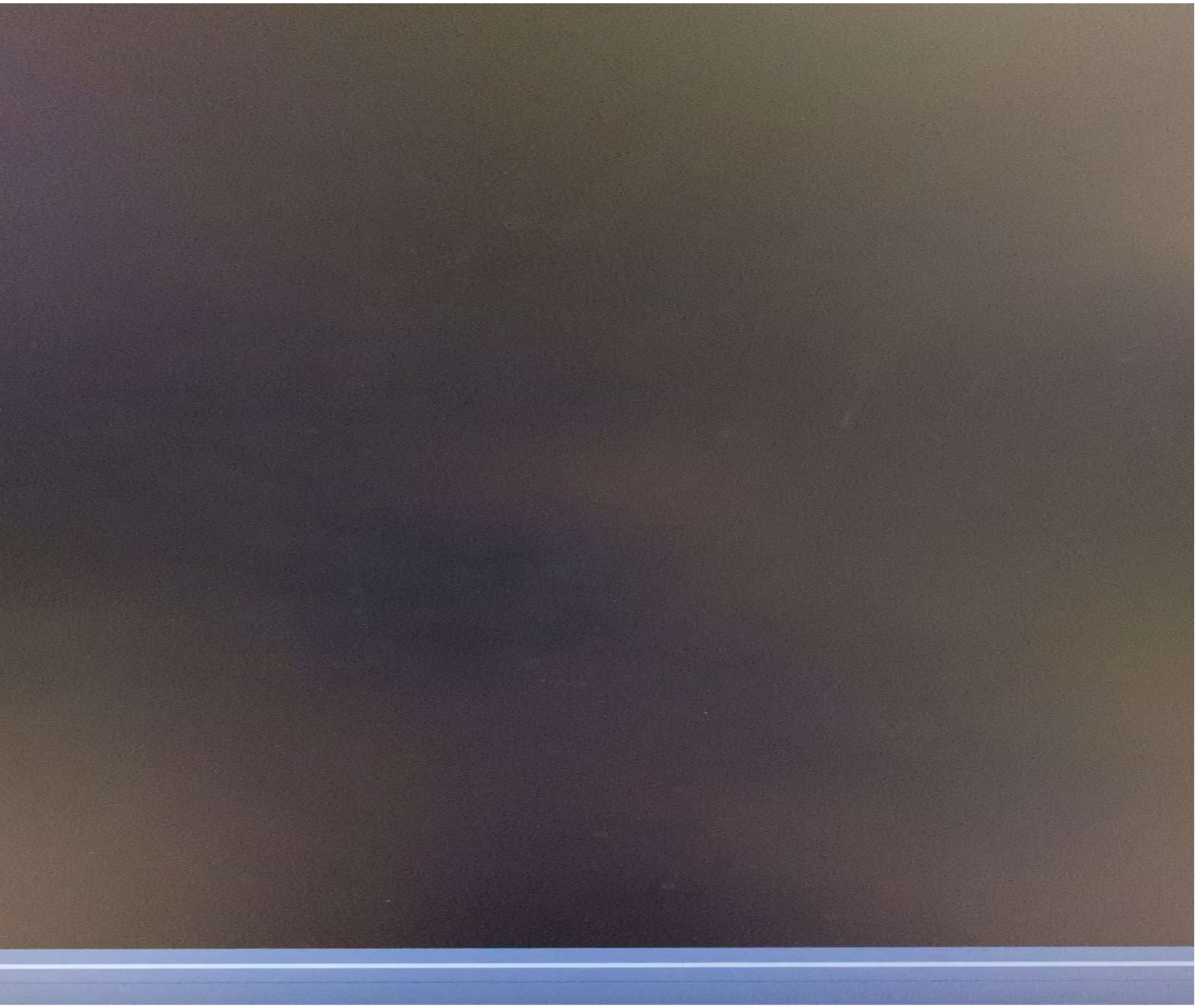
Materials Used:

- Aglilus30
- Vero Clear

PolyJet Photopolymers

The Stratasys Objet260 Connex

- Jets out material into ultra-thin layers
- Materials cured by UV light
- Can print from a wide range of mechanical properties – from flexible to rigid



Bill Of Materials

The total amount for one model

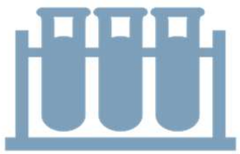
Material	Cost ($/gram)	Quantity Used (g)	Indv. Total
Agillus	0.75	12	9
VeroClear	0.7	184	128.8
Support	0.6	128	76.8
		Total	214.6

Budget

Total Budget				**$1000**
Rheometer	Status: ***On hand***	$15 per hour	25 hours	$375
Material	Status: ***On hand***	$0.60-$0.70 per gram	836 grams	$545.90
	Total Remaining	***$79.10***	***Total Spent***	***$920.90***

A total of 30 testing hours

5 hours were for compliance testing on the fluoroscope, also done through the lab but didn't require renting



A total of 35 samples and two full-size models were printed

Some samples were destroyed before / during testing, so more had to be printed

Future Work

- Adding an adventitia layer to the samples
  - Would require another set of donor samples to be tested.
    - This is due to the removal of the adventitia in the first study conducted.
- Using ratios of 30-40 and 40-50 shore hardness with the same 80-20% layering method.
- Update a new model design to be more anatomically correct physically and mechanically.
  - Total diameters of the left segment being adjusted.
  - Adding an adventitia layer
  - Reconstruct the layering to meet 1mm overall thickness, excluding 1.2mm RCA/LCA.

Questions