A Detailed Design Analysis of a Lumenally Delivered, Flexible, Balloon-Assisted, Sterile Endoscopic Overtube

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Abstract

The goal of this project was to develop a sterile surgical device for gaining peritoneal cavity access without external incisions via the body’s major natural orifices. Such Natural Orifice Translumenal Endoscopic Surgery (NOTES) interventions have recently received innovative attention as the next step in minimally-invasive surgery, however, the safety and efficacy depends greatly on sterility. The research for this thesis focused primarily on gastric interventions is divided into four main foci: tensile testing and determination of the most accurate material model for human gastric tissue, FEA analysis of the balloon dilation, experimentally validating these results using a silicone tissue phantom, and the paper design of a theoretical prototype.

Tensile testing the human gastric tissue provided the only material properties for the entire stress-strain curve known to the literature to be accurate. A series of tests were conducted on several different freshly donated organs. Statistical analyses were performed comparing the inner and outer layers, and the 0° and 90° orientation. These results showed that while visually different, the elastic portion of the stress-strain curve showed no statistical differences between layers or orientation.

A FE model was created in 2D axisymmetric and 3D to determine the minimum size incision needed to dilate large enough to allow passage for the device and endoscope without inducing irreversible damage to the tissue. Conclusions from tensile testing led to the material model being hyperelastic, homogeneous, and isotropic. ABAQUS Explicit was used to model the quasi-steady state problem and to more effectively manage contact definitions in the 3D simulation. The models were also simulated with a silicone material for experimental validation.

Using the same assumptions from the ABAQUS model, a physical experiment was performed with the silicone tissue phantom. From a circular incision of 10mm, several final diameters were tested. Rigid objects were used to dilate rather than balloons for ease of visualization. The surface had nodal coordinates drawn on the material and digital
images taken before and after dilation. Coordinates were extracted using xyExtract.exe, and strains calculated with a user defined MATLAB program.

Taking the above work into consideration, three different prototype designs were proposed. All three incorporate dual-donut balloons as the primary means of dilating the initial incision, holding the device in place, and providing a mechanical means for ensuring sterility while maintaining insufflation. The first embodiment simply incorporates dual balloons on the end of a PTFE sheath. The second utilizes a corkscrew-shaped singular balloon crimped in the middle to form the dual expansion zones. Finally, the last prototype design uses a second outer sheath to encapsulate both balloons which provides the dilatory force to the tissue, and acts as a long cylindrical balloon to stabilize the length of the sheath.
# Table of Contents

List of Tables........................................................................................................vi
List of Figures.........................................................................................................vii
1. Background and Literature Review................................................................. 1
   1.1 Background................................................................................................... 1
   1.2 Development Leading to NOTES............................................................... 2
   1.3 Lessons Learned from Laparoscopy........................................................... 8
   1.4 Benefits of NOTES..................................................................................... 13
   1.5 Peritoneal Cavity Access and Closure for NOTES................................. 17
       1.5.1 Transgastric NOTES........................................................................ 18
           1.5.1.1 Transgastric Access................................................................. 19
           1.5.1.2 Transgastric Procedures......................................................... 25
           1.5.1.3 Transgastric Closure............................................................... 29
       1.5.2 Transcolonic NOTES......................................................................... 33
           1.5.2.1 Transcolonic Access................................................................. 34
           1.5.2.2 Transcolonic Procedures......................................................... 36
           1.5.2.3 Transcolonic Closure............................................................... 39
       1.5.3 Transvaginal NOTES........................................................................ 44
           1.5.3.1 Transvaginal Access................................................................. 44
           1.5.3.2 Transvaginal Procedures......................................................... 45
           1.5.3.3 Transvaginal Closure............................................................... 47
       1.5.4 Transvesical NOTES........................................................................ 47
           1.5.4.1 Transvesical Access................................................................. 48
           1.5.4.2 Transvesical Procedures......................................................... 48
           1.5.4.3 Transvesical Closure............................................................... 50
   1.6 Patent Review............................................................................................. 51
       1.6.1 Overtube Patents.............................................................................. 51
       1.6.2 Needle Knife and Surgical Fastener Patents.................................... 55
   1.7 Problem Formulation............................................................................... 57
   1.8 Overview.................................................................................................... 58

2. Material Properties........................................................................................ 59
   2.1 Background............................................................................................... 60
   2.2 Human Gastric Tissue Uniaxial Pull-Testing.......................................... 70
       2.2.1 Initial Tensile-Testing Experiments.............................................. 70
       2.2.2 Bulk Tissue Material Properties................................................... 82
       2.2.3 Anisotropy of Human Gastric Tissue............................................ 86
       2.2.4 Gastric Tissue Layers Material Properties.................................... 91
   2.3 Silicone Tissue Substitute..................................................................... 98
   2.4 Overview.................................................................................................. 104

3. Finite Element Analysis (FEA).................................................................... 105
   3.1 Background on FEA............................................................................... 106
   3.2 Setting up the Finite Element Model.................................................... 111
       3.2.1 Material Model............................................................................ 111
           3.2.1.1 Human Gastric Tissue......................................................... 111
           3.2.1.2 Silicone Tissue Substitute.................................................. 120
List of Tables

Table 1-1: History of development leading up to NOTES .............................................. 3
Table 1-2: Comparison of down-time between open and laparoscopic surgeries3 .......... 9
Table 1-3: Adhesion formation after laparoscopic versus open liver resection32 .......... 10
Table 1-4: Risk factors for adhesions: ........................................................................... 10
Table 1-5: Results of pressure testing different styles of closing a gastrotomy (in psi)114 30
Table 2-1: Silicone sample cross-sectional area ............................................................. 100
Table 3-1: Material model assumption for different types of rubber216 ...................... 113
Table 3-2: Selection of biological tissues and their associated hyperelastic models in the
literature .................................................................................................................. 113
Table 3-3: Diameter change expressed as a percent of initial ID .................................. 146
Table 5-1: Comparison between MATLAB and ABAQUS FEA output ....................... 175
Table 5-2: Results from sensitivity study of xyExtract on stress in elements ............ 177
List of Figures

Figure 1-1: Step-by-step instructions for insertion of a PEG tube ........................................ 4
Figure 1-2: Miniaturized instruments (A) and access trocars (B) used during a mini-laparoscopic cholecystectomy. Standard 5 and 10-mm ports (B, left) are shown for comparison .................................................. 12
Figure 1-3: Surgical result of standard Roux-en-Y gastric bypass procedure ...................... 15
Figure 1-4: Bariatric patients can create difficulties for open and laparoscopic interventions ................................................................................................................................. 16
Figure 1-5: Difference between direct approach and retroflexion of an endoscope............. 19
Figure 1-6: Patent application 2003/0225312 device to capture stomach tissue for safe organ puncture ........................................................................................................ 21
Figure 1-7: Gastric incision being enlarged with a sphincterotome ....................................... 22
Figure 1-8: Process of balloon dilation for access to the peritoneal cavity ......................... 23
Figure 1-9: Process of STAT/SEMF for access into the peritoneal cavity through the stomach ............................................................................................................................... 24
Figure 1-10: Hybrid PEG/NOTES access technique ............................................................ 25
Figure 1-11: Multitasking platform designs .......................................................................... 28
Figure 1-12: Distal portion of the LSI prototype ................................................................ 30
Figure 1-13: Function of NDO plicator and resultant tab-closure ......................................... 31
Figure 1-14: G-prox tissue fastener and deployed fixation device ....................................... 32
Figure 1-15: T-tag deployment ............................................................................................ 33
Figure 1-16: Balloon to assist in containing stool contents ................................................. 35
Figure 1-17: TEM device used in NOTES procedures .................................................... 36
Figure 1-18: Direct NOTES route from the colon to upper quadrant organs ..................... 38
Figure 1-19: (A) Device tip before capture (hollow chamber), (B) Parallel needles advance (through tissue), (C) Needles engage distal ferrules attached to either end of single suture, (D) Central blades fires to create incision, (E) Needles retract, deploying suture in process, (F) Purse-string suture fully deployed, (G) Guidewire insertion through incision .................................................................................................................. 40
Figure 1-20: Colon suturing using T-tag method ................................................................ 41
Figure 1-21: Multi-Clip Applier in development by Ethicon Endo-surgery ....................... 42
Figure 1-22: Fully healed colon wall (internal and external) after closure with Multi-Clip Applier ................................................................................................................................. 42
Figure 1-23: View of distal end of Eagle Claw endoscopic suturing prototype .................. 43
Figure 1-24: Typical surgical setup needed for a NOTES procedure ................................. 51
Figure 1-25: Three overtubes used in NOTES interventions ............................................ 52
Figure 1-26: Short guidetubes used to bypass the oral cavity ............................................ 53
Figure 1-27: Additional overtube patent applications .......................................................... 53
Figure 1-28: Overtubes used for various endoscopic procedures ...................................... 54
Figure 1-29: Dual-balloon patents similar to the proposed NOTES overtube .................... 55
Figure 1-30: Two methods of T-tag insertion for active fixation of two layers of tissue ................................................................................................................................. 56
Figure 1-31: Delivered balloon-assisted endoscopic sheath .............................................. 57
Figure 2-1: Stretch ratio versus volume in circumferential, longitudinal, and radial directions ................................................................................................................................. 61
Figure 2-2: Full differentiation of the muscle layers

Figure 2-3: Fiber orientation, A) longitudinal layer (fibers split at black circle), B) circular layer, and C) the oblique layer

Figure 2-4: Stress vs. stretch ratio in the circumferential direction

Figure 2-5: Stress-strain plot for in vivo stomach experimentation

Figure 2-6: Location and orientation of test samples taken from rat stomach

Figure 2-7: Stress-stretch ratio graphs of the rat and rabbit stomach; c, circumferential; l, longitudinal; g, glandular; f, forestomach

Figure 2-8: General anatomy of stomach and surrounding tissue

Figure 2-9: General anatomy and longitudinal fiber orientation of porcine stomach when opened along greater curvature

Figure 2-10: Stress-stretch ratio of the porcine stomach from three anatomically different areas along two fiber orientations; A, antrum; C, corpus; F, fundus; circ, circumferential; long, longitudinal

Figure 2-11: Stress-strain plot from data from Egorov et al. for transverse gastric cadaveric tissue

Figure 2-12: Comparison between Gregersen et al. human gastric tissue testing and Zhao et al. porcine gastric tissue testing

Figure 2-13: Comparison between material properties from Gregersen et al., Zhao et al., and Egorov et al.

Figure 2-14: Warming pump and acrylic tank to warm refrigerated tissue up to 37 C

Figure 2-15: Human gastric tissue fixtured in MTS uniaxial testing machine

Figure 2-16: Optical measurement for tissue thickness

Figure 2-17: Preconditioning cycles outside layers of gastric tissue (test 5)

Figure 2-18: Results and average of initial testing of inner layers of cadaveric human gastric tissue

Figure 2-19: Results and average of initial testing of outer layers of cadaveric human gastric tissue

Figure 2-20: Pictorial process showing progression of tissue fracture during tensile testing

Figure 2-21: Results and average of testing bulk thickness cadaveric human gastric tissue

Figure 2-22: Comparison between uniaxial pull-testing of human gastric tissue

Figure 2-23: Comparison of uniaxial pull-test data of the human cadaveric gastric tissue to the data extracted from Egorov et al.

Figure 2-24: Comparison between test data and data from the literature by Egorov, Zhao, and Gregersen

Figure 2-25: Location and numbering of gastric tissue tensile testing for bulk thickness parallel to muscle fiber location

Figure 2-26: Bulk thickness tensile testing in direction of muscle fiber direction, performed 01-19-2010

Figure 2-27: All data from tensile testing gastric tissue in parallel with muscle fiber direction

Figure 2-28: All tensile test data including the average of gastric tissue parallel to fiber direction
Figure 2-29: Comparison between averages of tensile testing excluding various data sets .............................................................. 85
Figure 2-30: Comparison of orthogonal directions of human gastric tissue by Egorov et al. ................................................................. 87
Figure 2-31: Location and numbering of gastric tissue tensile testing for bulk thickness perpendicular to muscle fiber location ................................................. 88
Figure 2-32: Bulk thickness tensile testing perpendicular to muscle fiber direction, performed 01-19-2010 ............................................................. 88
Figure 2-33: All data from tensile testing gastric tissue in perpendicular with muscle fiber direction .......................................................... 89
Figure 2-34: Average curves of bulk tissue tensile testing in parallel and perpendicular to muscle fiber orientation ........................................ 90
Figure 2-35: Averages of data in parallel and perpendicular direction showing error bars ................................................................. 91
Figure 2-36: Composite and average of all tensile testing of inside layers ....................................................................................... 92
Figure 2-37: Composite and average of all tensile testing of outside layers .................................................................................... 92
Figure 2-38: Differences between inside and outside gastric tissue layers ....................................................................................... 93
Figure 2-39: Averaged data showing error bars ................................................................................................................................. 94
Figure 2-40: Skew and normal for inside and outside layers ............................................................................................................. 95
Figure 2-41: Regions of statistical significance overlaid on plot of areas of normality for inside and outside human gastric tissue ................................................................................................. 96
Figure 2-42: Material properties obtained from tensile testing 10A durometer silicone ............................................................................. 100
Figure 2-43: Tensile test data and average of 10A durometer silicone ................................................................................................. 101
Figure 2-44: Tensile test data and averages of 10A durometer silicone ................................................................................................. 102
Figure 2-45: Trendline showing material model for 10A durometer silicone ....................................................................................... 103
Figure 3-1: Truncated material properties to be used for FEA ........................................................................................................... 114
Figure 3-2: Initial uniaxial hyperelastic material model evaluation ........................................................................................................ 115
Figure 3-3: Uniaxial hyperelastic material model evaluation final results ................................................................................................. 116
Figure 3-4: Uniaxial hyperelastic model evaluation for full material data set ........................................................................................ 118
Figure 3-5: Hyperelastic material evaluation of 10A durometer silicone ............................................................................................. 121
Figure 3-6: Initial and final diameters of gastric tissue under radial expansion ....................................................................................... 122
Figure 3-7: Radial symmetry in model reduced down to a two-dimensional plane ............................................................................. 122
Figure 3-8: Quarter symmetry model for non-circular initial incision ................................................................................................. 124
Figure 3-9: Axisymmetric mesh ............................................................................................................................................................ 125
Figure 3-10: Thickness of three-dimensional model .......................................................................................................................... 126
Figure 3-11: Circular seeded mesh and close-up of mesh close to ID .................................................................................................. 126
Figure 3-12: Partitioned physical model of linear slit and close-up showing various partitions ........................................................................................................ 127
Figure 3-13: BC's of axisymmetric model ............................................................................................................................................... 128
Figure 3-14: 3D model used in FEA balloon expansion of gastric tissue ................................................................................................. 129
Figure 3-15: Effect of tool speed on deformed shape .......................................................................................................................... 132
Figure 3-16: Impact velocity influence on local or global deformation .................................................................................................. 133
Figure 3-17: Effect of mass scaling on FEA simulation results ............................................................................................................. 133
Figure 3-18: Difference between standard (Lagrangian) meshing and adaptive meshing (ALE) ................................................................................................................................. 134
Figure 3-19: Effect of adaptive meshing on deformed object during simulation ..................................................................................... 134
Figure 3-20: Close-up of distorted ID, pressure = 200,000Pa
Figure 3-21: Stress contour plot of pressure=55,000Pa, Y-symmetry
Figure 3-22: Stress contour plot of pressure=55,000Pa, full thickness
Figure 3-23: Radius 0.005m, displacement 0.00152m
Figure 3-24: Radius 0.005m, displacement 0.00288m
Figure 3-25: Radius 0.005m, displacement 0.00288m, plastic strain
Figure 3-26: Stable displacement =0.00282m (top), and buckling displacement =0.00283m (bottom)
Figure 3-27: Close-up of ID of buckling displacement = 0.00283m
Figure 3-28: Buckling of tissue on deformation of 0.00288m
Figure 3-29: Von Mises stress contour plot, ID=.0065m, displacement=.0035m
Figure 3-30: Von Mises stress contour plot, full thickness, ID=.0066m,
displacement=.0034m
Figure 3-31: Von Mises stress contour plot, ID=.0083, displacement=.0042
Figure 3-32: Von Mises stress contour plot, full thickness, ID=.0083, displacement=.0042
Figure 3-33: Equivalent lengths (L_e) for beam buckling
Figure 3-34: Axisymmetric silicone model, ID=10mm, displacement=10mm, silicone
Figure 3-35: Hourglassing in shell elements during radial expansion
Figure 3-36: Deforming tissue with steel balloon
Figure 3-37: Steel balloon dilation; vertical displacement (left), 45° displacement (right)
Figure 3-38: Cone dilation of human gastric tissue
Figure 3-39: Deformed plot of initial ID=16.6mm, final ID=25mm, Neo Hookean material model
Figure 3-40: Material evaluation and stability information - gastric tissue
Figure 3-41: Three-dimensional dilation of silicone model, ID=10mm,
Deformation=10mm
Figure 3-42: Linear incision, 10mm tall, 2mm wide
Figure 3-43: Close-up of distal end of deformed slit
Figure 3-44: Undeformed and deformed contour plot of 10mm high by 1mm wide
e nlarged to 4mm
Figure 4-1: SolidWorks depiction of experimental setup
Figure 4-2: Sample color-map plot
Figure 5-1: Lumen-mounted dual-donut balloon supplied by Fast Forward Medical...
Figure 5-2: End-view of balloon dilation of silicone
Figure 5-3: Items used for rigid dilation
Figure 5-4: Silicone mounted in test apparatus with 14mm object
Figure 5-5: Buckling of silicone under high deformation, 20mm
Figure 5-6: Quarter-symmetry silicone deformed nodes defined for digital extraction
Figure 5-7: Stress contour plot of quarter-symmetry: initial ID=10mm, final ID=20mm
Figure 5-8: Deformation of silicone while being punched
Figure 5-9: Comparison between MATLAB and ABAQUS output for 20mm dilated ID
Figure 5-10: Close-up of silicone ID, deformed ID=20mm
Figure 6-1: Donut balloons created by FP Solutions Group: deflated (left), inflated (right) .............................................................................................................................................................................................. 182
Figure 6-2: Two different methods for filling balloons, Prototype design #1 .......... 183
Figure 6-3: Prototype Design #2..................................................................................... 184
Figure 6-4: Expanded view of the one piece donut balloon ........................................ 185
Figure 6-5: Prototype #3 before balloon expansion....................................................... 186
Figure 6-6: Prototype #3 after balloon dilation.............................................................. 186
Figure 8-1: Sample finite element shown with its local forces and displacements orientated θ radians from global zero .............................................................................. 206
1. Background and Literature Review

Introduction

This chapter aims to provide an introduction to Natural Orifice surgery and why such radically new surgical techniques are necessary. Subsequent to a brief background discussing the motivation behind the work in this thesis, a detailed literature review and historical perspective is given on the field of NOTES. Finally, to conclude this chapter, an overview of the remainder of the work is established.

1.1 Background

Crossing the gastrointestinal tract has long been associated with sepsis, peritonitis, and high mortality rates. A perforated peptic ulcer was first recognized in 1799, and in 1892 Dr. Ludwig Heusner in Germany was the first to report successful repair of a gastric ulcer. In World War I, the mortality associated with intestine and colon injury was approximately 66% and 59% respectively. Surgeons have also recognized early on that a perforation of the gastrointestinal tract must be closed quickly and completely in order to avoid complications.

More than two decades ago, laparoscopy revolutionized the field of general surgery. Now another “disruptive technology” may radically alter the field once again. NOTES is an experimental technique that involves performing surgical procedures with a flexible endoscope through a natural orifice such as the mouth, rectum, urethra, or vagina. Natural orifice surgery removes the need to create incisions across the abdominal wall, thus minimizing or even eliminating post-operative pain, abdominal scars, and complications such as incisional hernias and adhesions. The initial animal and clinical test have shown enticingly positive results – despite the lack of specialized equipment and standardized procedures. Gastroenterologists and laparoscopic surgeons alike are pushing for new devices to further advance these new surgical techniques.
In 2005 the American Society for Gastrointestinal Endoscopy (ASGE) and the Society of American Gastrointestinal & Endoscopic Surgeons (SAGES) formed a working group to ensure safety and responsibility in advancing NOTES. They collaboratively produced a white paper outlining potential barriers to clinical practice: access and closure of peritoneal cavity, infection prevention, development of suturing and anastomotic device, special orientation, development of multitasking platform, management and control of complications, physiologic untoward events, compression syndromes, and training. Though NOTES materialized through the advancements of surgical techniques, many of the described barriers call for an increased effort from medical device engineers to meet the needs of this burgeoning area of research.

NOTES can potentially replace many laparoscopically performed surgeries and ease the rigors of difficult surgical procedures – such as biliary duct drainage (ERCP) in a patient with stomach bypass. As natural progression in minimally invasive surgery, NOTES raises a multitude of problems with separating the sterile peritoneal cavity from the non-sterile access locations. Systemic antibiotics, lavaging – with sterile saline and antibacterial solutions – and sterilized instruments have reduced infection rates of the transluminal approach. Even still, there exists a strong desire to reduce iatrogenic infections to at least that of the gold-standard of laparoscopic surgery.

1.2 Development Leading to NOTES

Using a literal definition, the first description of a NOTES procedure was a culdoscopy performed by Russian Dr. Dmitri Von Ott on April 19, 1901. In this procedure, an endoscope scope was inserted through the posterior fornix of the vagina for examination of the viscera of the female pelvic cavity. Thus, natural orifice surgery is literally over a century old. A culdoscopy, however, is limited to females and has traditionally been only used to visualize the lower pelvic anatomy. In the early 1930’s, innovation on rigid ureteroscopes made transurethral prostate surgery available for the first time. Dr. Nathaniel Alcock performed 50 cases of transurethral resection of the prostate (TURP). Though the mortality rate was 24%, this was still much better than open surgeries at the time. Through the next century, both rigid laparoscopes and flexible endoscopes were
developed for use in both procedures. Table 1-1 shows the major papers outlining the development, or acceptance of NOTES in the medical community.

<table>
<thead>
<tr>
<th>Year</th>
<th>Author</th>
<th>Procedure</th>
</tr>
</thead>
<tbody>
<tr>
<td>1901</td>
<td>Von Ott³</td>
<td>First culdoscopy, rigid scope inserted through the vagina</td>
</tr>
<tr>
<td>1931</td>
<td>Alcock¹¹</td>
<td>Transurethral prostate surgery developed</td>
</tr>
<tr>
<td>1944</td>
<td>Decker et al.¹²</td>
<td>First reported culdoscopy</td>
</tr>
<tr>
<td>1975</td>
<td>Cheng et al.¹⁹</td>
<td>Local anesthiesia accepted for culdoscopic interventions</td>
</tr>
<tr>
<td>1980</td>
<td>Gauderer et al.¹⁴</td>
<td>First PEG tube placement without laparotomy</td>
</tr>
<tr>
<td>1985</td>
<td>Kozarek et al.¹⁶</td>
<td>Endoscopic drainage of pancreatic pseudocysts</td>
</tr>
<tr>
<td>1992</td>
<td>Wiersema et al.¹⁷</td>
<td>Endoscopic ultrasound with needle aspiration cytology</td>
</tr>
<tr>
<td>1999</td>
<td>Paulson et al.¹⁸</td>
<td>Pelvic culdoscopic with laparoscopic coorelation</td>
</tr>
<tr>
<td>2000</td>
<td>Kalloo et al.²⁵</td>
<td>Transgastric peritoneal interventions in pigs, abstract</td>
</tr>
<tr>
<td>2003</td>
<td>Tsin et al.²²</td>
<td>First culdolaparoscopic cholecystectomy</td>
</tr>
<tr>
<td>2003</td>
<td>Halim et al.¹³</td>
<td>Transgastric NOTES in human model, India</td>
</tr>
<tr>
<td>2004</td>
<td>Kalloo et al.²⁴</td>
<td>Transgastric NOTES interventions in pigs, full paper</td>
</tr>
</tbody>
</table>

Table 1-1: History of development leading up to NOTES

The next major achievement for natural orifice surgery came in 1980 when Dr. Gauderer et al. endoscopically placed a gastric feeding tube without the use of laparotomy.¹⁴ Also known as a percutaneous endoscopic gastrostomy (PEG) tube, it can be placed temporarily for acute conditions or permanently in chronic disabilities. Until this time, gastrostomy feeding tubes were inserted surgically. Many times patients needing these tubes are high-risk for either general or local anesthesia, or brain damaged children who have musculoskeletal deformations making surgery difficult. The original method uses readily available equipment found in a typical operating room. Skin at the chosen abdominal site is anesthetized and a 3-5mm slit made. A gastroscope is inserted through the mouth, air is injected to move any organs, and the scope is brought to contact with the abdominal wall interior from the slit. A 16-gauge smoothly tapered intravenous cannula is then pushed quickly through all remaining layers. Next, a suture thread is advanced through the scope and tied securely to the cannula. The cannula is then removed through the mouth, a Pezzer catheter is attached and pulled back through the abdominal incision via the suture. The finished result is a direct access port to the stomach for the purpose of feeding. See Figure 1-1 for an illustration of this technique. Though not puncturing the
gastrointestinal lumen into the peritoneal cavity, this new procedure still provided the groundwork for acceptance to breach the stomach wall in a controlled manner.

Semm’s review of the literature relating to gynecological abdominal procedures in 1983 summarized the advances into the peritoneal cavity via transvaginally. Routine surgeries listed at that time included: tubal ligation, tubal therapy of ectopic pregnancy, ovarian biopsy, ovariectomy, and management of adhesions. Semm also reported more radical interventions such as appendectomy, lysis of bowel adhesions and omental adhesiolysis had also been performed. These operations reduced hospitalization by over 50%, and cut the healing time by 75% while only having a complication rate of 2%, when compared to open procedures. This clearly demonstrates interventions into the peritoneal cavity via a natural orifice had become well established by the early 1980’s. Despite the initial successes of natural orifice surgery in the gynecological field, the next innovations would come from the GI suite.

Two other notable NOTES precursory procedures were carried out by Kozarek et al. in 1985, and Wiersema et al. in 1992 which endoscopically targeted intra-abdominal organs via the gastrointestinal tract. The Kozarek paper describes a procedure in which drainage of pancreatic pseudocysts was accomplished endoscopically. Typically drained externally, or internally with cystogastrostostomy, the authors discussed a method of

Figure 1-1: Step-by-step instructions for insertion of a PEG tube

![Step-by-step instructions for insertion of a PEG tube](image)
draining with endoscopic cystostomy. Many times pancreatic cysts are asymptomatic, but when they develop complications such as bleeding, swelling, or biliary obstruction they must be drained. In this method, Kozarek et al. created a small incision in the posterior gastric wall thereby draining the cyst into the stomach. The cyst drained adequately and the patients recovered well with the administration of oral antibiotics to avoid infectious complications. This natural orifice surgery was uncomplicated due to the desired structure being directly adjacent to the stomach wall, further supporting transgastric surgery techniques.

Wiersema et al. adopted the acceptance of transluminal procedures to fine needle aspiration cytology. Whereas endoscopic ultrasound (EUS) is a readily accepted mode of characterizing submucosal masses, it is unable to give histological details. Some masses can be problematic for standard biopsy techniques, however. The authors realized that by navigating to the masses endoscopically and using fine needle aspiration cytology, they were able to take samples of masses exterior the lumen. The lesion is first identified with EUS. The endoscope is placed near the desired mass and a needle is inserted through the wall of the lumen into the mass. Once penetration has occurred, suction is placed on the needle while the endoscope is vigorously moved inside the lesion in 3mm to 5mm strokes. Suction is released, and the needle withdrawn and the contents of the hollow needle is then analyzed in the lab. This procedure was used as a minimally invasive option to investigate difficult-to-reach lesions. Though neither Wiersema’s nor Kozarek’s studies are considered a natural orifice surgery as recognized today, these articles show a trend in deviating from the age-old directive of endoscopy and surgery to never deliberately perforate the gastrointestinal lumen.

In a more recent study conducted by Paulson in 1999 et al. a group of n=8 females underwent a culdoscopy in addition to a laparoscopy. For the first time, an endoscope was inserted fully into the peritoneal cavity for the purpose of comparing laparoscopic surgery to a natural orifice approach for certain pelvic procedures requiring crossing the reproductive organ walls: fibrioplasty, tubal ligation, and endometriosis for example. The culdoscopy findings were correlated 100% with laparoscopy, proving the ability of
flexible endoscopes to adequately visualize internal anatomy for accurate clinical diagnoses. Additionally, though established in 1975 by Cheng et al., Paulson reiterated an important potential benefit of NOTES over laparoscopic procedures – the ability for local anesthesia to be sufficient for interventions thereby eliminating the need for general anesthetetics and allowing even operative cases to be performed as an outpatient procedure.\textsuperscript{19,18,20}

Shortly thereafter, Dr. Reddy and Dr. Rao performed unpublished procedures in Hyderabad, India exploring purposefully crossing the gastrointestinal tract into the peritoneal cavity. This research group significantly pushed the envelope by performing the first 7 transgastric appendectomy in humans with good results in 2003.\textsuperscript{4} This unpublished report proves technical feasibility of peritoneal interventions via an oral cavity.\textsuperscript{21}

Then, in 2003 Tsin published a report of a culdolaparascopic cholecystectomy.\textsuperscript{22} An 81-year old woman presented herself with uterine prolapse and symptomatic cholelythiasis. Instead of forcing the patient to undergo two separate procedures, both were resolved at the same time. Following the removal of the uterus, a 12mm diameter cannula was placed across the cul-de-sac for scope access of the peritoneal cavity and subsequent cholecystectomy. Three additional laparoscopic ports – a 10mm umbilical and two 5mm upper-quadrant – were also used thereby making the procedure a laparoscopic-assisted NOTES. The resected organ was removed without incident through the vaginal port. Laparoscopic-assisted cholecystectomy via a transvaginal route was further substantiated in 2007 when Marescaux et al. published their paper with similar results.\textsuperscript{23} Reported as a true natural orifice surgery, Marescaux used a double-channel videogastroscope for the majority of the surgery, and the 2mm laparoscopic port was only used for insufflation and organ retraction.

Though Dr. Reddy and Dr. Rao have unpublished reports of performing the first natural orifice surgery on humans in India coming from 2003 Dr. Anthony Kalloo – Gastroenterologist from Johns Hopkins University in Baltimore Maryland – is credited as being the father of natural orifice transluminal endoscopic surgery. NOTES was pushed
to the forefront of the medical community when a full article by Kalloo et al. was published in Gastrointestinal Endoscopy in 2004.\textsuperscript{4,24} Initially published as an abstract in Gastroenterology in 2000, the full article described Kalloo et al. performing a transgastric peritonoscopy for the sole purpose of interventions in the peritoneal cavity.\textsuperscript{25,24} In a porcine model, an acute and long-term study of transgastric exploration and liver biopsies demonstrated the “technical feasibility and the safety of an endoscopic approach to the peritoneal cavity.”\textsuperscript{24} Using an electrically-charged cutting tool called a needle-knife, a 2mm incision was created in the stomach wall and expanded with a pull-type sphincterotome or dilation balloon. The researchers then inserted a guidewire under fluoroscopic assistance and a forward-facing endoscope was advanced over the wire. The peritoneal cavity was insufflated for ease of peritoneal cavity exploration. For the long-term studies, all instruments were sterilized and an additional guidetube placed over the endoscope to aid in aseptic conditions. Gastric incisions were closed with endoscopic clips. All procedures were performed without incident. Acute models showed no injury to adjacent organs or significant bleeding from gastric wall puncture. Long-term models resumed normal diet and exercise within 24 hours and gained weight during the 14-day study span. Upon necropsy, biopsy sites had healed well, complete gastric wall healing was found, and no major post-operative complications were found. Kalloo showed for the first time, in the porcine animal model, that endoscopic access to the peritoneal cavity for diagnoses and interventions was feasible. This paradigm-shifting paper received worldwide attention as a radical new alternative to minimally invasive surgery.

Despite the initial success and obvious development of natural orifice surgery, prior to 2004, the procedure mostly flew below the radar of the medical community. The reasons for this are not entirely clear, however two explanations stand out. First, throughout history, crossing into the peritoneal cavity from a non-sterile field has been perceived with inflammation, infection, and other clinical complications.\textsuperscript{26,27,28} Gastrointestinal tears can be created from both upper and lower gastrointestinal endoscopy and present a complication for traditional open and laparoscopic surgeries. Such complications typically called for immediate surgical intervention to close the perforation. Therefore, attempting to purposefully access the peritoneal cavity via natural orifices was considered
taboo. Secondly, the original natural orifice surgeries were basically extensions of previously accepted procedures. Laparoscopic-assisted culdoscopy cholecystectomy, for example, was a marriage of two well developed interventions with a slight twist. The purpose for such surgeries was to creatively treat patients with unique clinical presentations on a case-by-case basis. These physicians were not publishing with the intention of radically changing the surgical field, but rather to share experiences and show what is possible. Physicians such as Reddy, Rao, and Kalloo saw the changes that laparoscopy made to minimally invasive surgery, observed these preliminary articles showing technical feasibility, and sought to join the two and bring NOTES to the forefront of surgical advancement as the future of peritoneal interventions.

1.3 Lessons Learned from Laparoscopy

Historically, interventions dealing with the organs of the peritoneal cavity required open surgery. Unless the organs were easily accessible via flexible or rigid endoscopes – such as the stomach, colon, vagina, and parts of the upper and lower intestine – the only way to reach more remote organs was through creating a large incision in the patient’s anterior abdominal wall. Open surgery allows surgeons to easily visualize the complete abdominal anatomy making the operation and managing potential complications straightforward.

Laparoscopic surgery required surgeons to develop new skills, performing surgery through trocars. However, laparoscopic surgery has multiple advantages over open surgery: less post-operative pain, earlier discharge, faster patient mobilization, superior cosmetic results, and reduced impact on the healthcare system.

Laparoscopic surgery has taken cholecystectomy, for example, from a procedure that required 5-7 days of hospitalization and up to 4-6 weeks at home to being back to work in 1-2 days after only a day in the hospital. This is shown in Table 1-2 below. The economic impact on medical facilities and patient’s employers is staggering. The hospital can perform many more surgeries and each patient requires a fraction the resources. At the
work place, employers are not left shorthanded while paying sick time to employees for weeks.

<table>
<thead>
<tr>
<th></th>
<th>Open</th>
<th>Laparoscopic</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Hospital Stay</strong></td>
<td>5 – 7 days</td>
<td>0 – 1 day</td>
</tr>
<tr>
<td><strong>Return to work</strong></td>
<td>4 – 6 weeks</td>
<td>1 – 2 days</td>
</tr>
</tbody>
</table>

Table 1-2: Comparison of down-time between open and laparoscopic surgeries

Due to the significantly faster healing time, the amount of pain medication needed after a laparoscopic procedure is also reduced. Pain medicines used after intensive open surgeries are often very strong narcotics which can produce undesirable side-effects. Many patients dislike these symptoms and would prefer to take less medicine if possible. Stoker et al. published a study directly comparing the outcomes of laparoscopic versus open repair of an inguinal hernia in 150 patients. They found that return to normal activity and work after open surgery was achieved in 7 days and 28 days respectively, compared to only 3 days and 14 days for laparoscopic repair. This faster return to activity and work may have been due to the patient’s ability to function without the constant presence of pain. This same study also recorded the amount of pain and corresponding pain medicine used in each group. The open surgery group had a mean pain score of 3.1 and self administered a median of 18 325mg tablets of co-proximal. Laparoscopic surgery patients experienced a significant decrease in pain with a mean score of 1.8 and took only 6 pain pills. This quantitative study proved the reduction in pain for laparoscopic surgery over open for inguinal repair. We can extrapolate from these results to be characteristic of the reduced invasiveness from standard to laparoscopic surgery.

In addition to decreased post-operative pain and earlier patient mobilization, laparoscopic surgery is shown in Table 1-3 to have a greatly reduced incidence of adhesion formation. Adhesions are bands of scar tissue that form beyond the site of incision, and sometimes even in unrelated parts of the peritoneum. They can form constrictions of the small intestine resulting in blockage and constipation as well as bind up other internal organs, limiting motion so movements pull awkwardly and result in abdominal pain. It has also been thought that adhesions may cause female infertility by the blocking the
Many of the listed risk factors are decreased when undergoing laparoscopic interventions instead of open surgery. Burpee et al. found a very significant reduction in adhesions when performing liver resection; only 12 adhesions were found for laparoscopic versus 35 for open surgery. This is likely from reduced incision size, reduced organ irritation from exposure, and maintained immunologic function in laparoscopic surgery. Some of the notable risk factors for adhesion formation are shown in Table 4-4.

| Table 1-3: Adhesion formation after laparoscopic versus open liver resection |
|---------------------------------|-----------------|----------------|
| **Risk Factors for Adhesions** | **Laparoscopic** | **Open** | **p** |
| **Number of adhesions** | 12 (n = 7) | 35 (n = 7) | 0.0001 |
| **Site of adhesions** | | | |
| Parietal | 1.7 | 5 | |
| Visceral | 9 | 17 | |
| **Vascularization** | | | |
| Avascular | 11 | 9 | |
| Vascularized | 1 | 26 | |
| Mean/adhesion | 0.21 ± 0.2 | 0.73 ± 0.4 | 0.0028 |
| **Thickness** | | | |
| < 3 mm | 11 | 19 | |
| > 3 mm | 1 | 16 | |
| Mean/adhesion | 1.07 ± 0.2 | 1.41 ± 0.3 | 0.0002 |
| **Teariness** | | | |
| Type I | 1 | 2 | |
| Type II | 10 | 17 | |
| Type III | 1 | 16 | |
| Mean/adhesion | 2.1 ± 0.2 | 2.4 ± 0.3 | 0.0003 |
| **Total score (mean)** | 7.9 ± 5 | 27.7 ± 6.9 | 0.0001 |

The nature of reduced adhesion formation from laparoscopic surgery over natural surgery becomes apparent after reviewing the above list. Many are physiological responses due to the outcomes of surgery. There is significantly less tissue incision, and therefore decreased inflammatory response with laparoscopic procedures. The tissue maintains
hydration and viscera is handled less. It has also been found that early patient mobilization after laparoscopic surgery is a contributing factor to fewer adhesions. Though not all risk factors can be mitigated from laparoscopic surgery, reducing external incisions, excessive manipulation, and tissue dehydration has significantly reduced the occurrence of adhesions.

Infectious complications comprise the majority of post-operative morbidity for abdominal surgery.\textsuperscript{37} Laparoscopic surgery was long accepted to be superior to open surgery for reduced infection rates. However, until in a \textit{Surgical Endoscopy} study published in 2008 a quantitative assessment of this decrease was lacking. Brill et al. published a retrospective analysis of 11,662 patients comparing infection rates for open and laparoscopic cholecystectomy, appendectomy, and hysterectomy procedures.\textsuperscript{38} A statistical analysis was conducted to account for variations of gender, age, insurance, complexity of admission of presentation, admission through the emergency department, and hospital case mix index. The results were startling. Although laparoscopic appendectomies did not show a statistically lower infection rate, laparoscopic cholecystectomy and hysterectomy reduced the rates of nosocomial infections by greater than 50\% over open surgery, and had a 65\% reduction in hospital readmissions (p<0.01). All types of infections including wound, bloodstream, respiratory tract, and urinary tract were shown to be lower for a laparoscopic cholecystectomy.\textsuperscript{38}

In addition to macroscopic infection rates, the switch to laparoscopic surgery reduces systemic physiologic stress on the patient. It is well established that surgical interventions have a significant impact on the human immune system.\textsuperscript{39} One key marker of acute-phase physiologic response, the C-reactive protein, shows 20-fold increase after 4 to 12 hours after open surgery and peaks at 24 to 72 hours.\textsuperscript{40} After laparoscopic procedures the C-reactive proteins only exhibit a 5-fold increase.\textsuperscript{41,42}

Immunosuppression is another well established physiological response to surgery.\textsuperscript{39,43,44,45} The degree of suppression appears to be related to the degree of invasiveness.\textsuperscript{46} Studies have shown total leukocyte activity is significantly increases during open surgery, but not in patients in laparoscopic cholecystectomy.\textsuperscript{47,48}
Additionally, it has been shown that delayed type hypersensitivity (DTH), an immune system T-cell response, is significantly diminished following an open surgery. Krokel et al. evaluated the differences between DTH in rats undergoing laparotomy versus laparoscopy and insufflation. Trokel showed that laparoscopy resulted in an unchanged DTH response whereas rats which underwent laparotomy had a significantly diminished DTH response. The same result has been found in human patients, where DTH was found to be reduced 67% in open surgery compared to 0% in laparoscopic surgery.

Despite the minimally invasiveness of laparoscopic surgery, surgeons have been making a push to reduce the impact on patients even further by developing mini-laparoscopic techniques and tools, as seen in Figure 1-2. Standard laparoscopic tools use 10mm and 5mm trocars for tools, visualization, and organ resection. During mini-laparoscopy, several of the 5mm trocars are replaced with 2mm trocars to reduce trauma and incision size. Though no statistically significant differences were noted for post-operative pain in mini-laparoscopic over standard laparoscopic surgery, on day 28 90% of patients had no pain compared to only 74% respectively. The cosmetic result was also found to be significantly better for mini laparoscopic procedures, with mini-laparoscopy scoring 38.9±2.1 over standard which received a score of 28.9±5.7 when evaluated by a study nurse.

Figure 1-2: Miniaturized instruments (A) and access trocars (B) used during a mini-laparoscopic cholecystectomy. Standard 5 and 10-mm ports (B, left) are shown for comparison.
1.4 Benefits of NOTES

Looking at the trend from open surgery, to laparoscopic surgery, to mini-laparoscopic surgery, it becomes obvious that as the invasiveness of the procedure decreases, so does the recovery time and physiological stress. Our understanding is that moving to an incision-less surgery – NOTES – that these same trends will continue. Laparoscopic surgery reduced hospital stays for a peritoneal intervention to a mere fraction of what they are if the same procedure had been done using open surgery. Though the hospital stay and recovery time of a laparoscopic surgery are already quite low and there hasn’t been a decreased time shown in min-laparoscopy, researchers are optimistic the transition to natural orifice surgery could result in reducing these times. Instead of a cholecystectomy or appendectomy requiring weeks of recovery at home, one could possibly have the procedure in the morning and be at work by lunch.

Open surgery results in a great deal of pain from large incisions through the skin and major muscle groups. The decreased incisional sizes in laparoscopic surgery greatly mitigated this. Mini-laparoscopic surgery reduced pain even more. Dr. David Rattner, MD professor of surgery at Harvard Medical School and Chief of general gastrointestinal surgery at Massachusetts General Hospital recently commented on a large study of 180 NOTES cholecystectomies conducted in Brazil. The complication rates were found to be analogous when compared to laparoscopic studies, but the most startling discovery was the dramatic reduction in pain medicine used.54 The amount of internal disruption is quite similar between laparoscopic and NOTES and the internal irritations will likely be very comparable. Additionally, the trocars placed in laparoscopic surgery disrupt subcutaneous structures like muscles which also cause the patient pain during the recovery period. However, since the skin remains intact in NOTES procedures, there are no topical sites to cause the patient discomfort or pain, thereby lessening the pain medication used post-operatively.

As discussed already, moving from open to laparoscopic surgery results in a reduced number of adhesions. Because natural orifice surgery does not have external incisions, there lies a possibility of a reduced number of adhesions. NOTES involves even fewer
incisions, less tissue inflammatory response, and earlier mobilization after surgery – all major contributors to adhesion formation. In addition to reduced production of adhesions, NOTES may be a viable option of treating individuals already suffering from them. The current method of adhesiolysis usually involves laparoscopic interventions. This procedure has the risk of producing more adhesions, thereby creating a cyclic problem. If the theory of reduced adhesion formation after NOTES surgery proves correct, those suffering from adhesions could finally have a permanent method of removal. Through reduced formation and nearly formation-free removal, adhesions may become a problem of the past.

Incisions provide an access port for bacterial infections, either in the incision itself or inside the peritoneal cavity. Wound infection remains a risk associated with laparoscopic procedures. Topical wounds must be cared for by the patient at home to ensure infections do not develop. Natural orifice surgery does not have any topical incisions the patient is responsible for during the recovery period, thereby effectively eliminating this mode of infection. However, NOTES procedures have the inherent infection risk of crossing into the peritoneal cavity via an access organ which may contain many contaminants. These same risks are seen in patients undergoing a gastrojjenostomy, or stomach bypass seen in Figure 1-3. During this surgery the contents of both the stomach and small intestine are exposed to the peritoneal cavity at some point. Measures are taken to mediate the risk of spillage and the manipulation and time exposed of openings is minimized. An additional risk is of a leakage of the staples developing during recovery allowing stomach contents to gain access to the peritoneal cavity. Natural orifice surgery has the advantage of creating a much smaller irregularity in the access organ wall which should help minimize this risk. Though NOTES will be technically challenging to access the body in a sterile manner through non-sterile organs, research is being performed to provide a means of sterile access to the peritoneal cavity.
An additional benefit to natural orifice surgery involves being able to perform peritoneal interventions in bariatric patients.\textsuperscript{3,21} Figure 1-4 shows an example of such a patient. Both open and laparoscopic surgeries are currently performed on the morbidly obese, sometimes with great difficulty. In patients with thick fatty layers, trocars may barely reach the peritoneal cavity and are subject to slipping out (conversation with Dr. Leslie HCMC). This thick layer of tissue also places a great deal of resistance to surgeons attempting to manipulate tissue. Additionally, a relatively simple procedure such as and ERCP in a patient with stomach bypass becomes an arduous task. The bile duct drains into the small intestine just distal to the duodenum. Typically, accessing the bile duct is a simple matter of passing an endoscope through the stomach into the small intestine. In patients that underwent a stomach bypass, the upper portions of the small intestine are only accessible by navigating the endoscope down the Roux limb, then back up the intestine back to the bile duct. NOTES would allow the surgeon to pass outside the proximal stomach pouch, back into the bypass portion of the stomach, and proceed as normal.
An additional implication of natural orifice surgery for the morbidly obese is to avoid complications associated with insufflation during laparoscopic surgery.\textsuperscript{61} Nguyen et al. performed a search of the literature of bariatric surgeries from 1994 to 2003 examining the physiological effects pneumoperitoneum has on the morbidly obese. They found that due to the additional weight on the abdomen that must be lifted in order to create adequate viewing during surgery, obese patients see an intra-abdominal pressure 2 to 3 times that of non-obese patients.\textsuperscript{57} This puts the obese at a higher risk of intraoperative complications due to this increased pressure; risks such as enhanced venous stasis, reduces intraoperative portal venous blood flow, decreased intraoperative urinary output, lowered respiratory compliance, increased airway pressure, and impaired cardiac function.\textsuperscript{57} Natural orifice surgery may not need as high of pneumoperitoneum in order to maintain adequate internal visualization; thereby effectively reducing the risk of any surgical intervention to this target population.

Similar to the decrease in immunosuppression between laparoscopic surgery and open surgery, researchers theorize a similar result for NOTES interventions. The immune system response was at least partially correlated to the amount of disruption to the body. Natural orifice surgery will eliminate any external incisions in the skin reducing trauma and immune system response to reseal the skin barrier. The internal trauma will likely be similar to laparoscopic, but due to eliminated external incisions the overall physiological stress to the body will be reduced. It remains possible that part of the recovery and
overall feeling after surgery is due to reinstatement of equilibrium in the body. Additionally, to the morbidly obese, natural orifice surgery not only provides a safer form of surgery, it allows for surgical innovation to more easily provide a higher standard of care in a less invasive manner. Less stress means faster recovery. NOTES will have less stress than any other known method of peritoneal surgery to-date.

1.5 Peritoneal Cavity Access and Closure for NOTES

The four access organs – stomach, colon, vagina, and bladder – can be separated into major and minor access points. The vagina, stomach and colon are classified as major because due to its large size, an entire NOTES procedure could be performed through this one opening. Quite obviously, the vagina is a major access organ limited to the female population. The bladder is a minor access organ and is predominantly used for supporting the major access organ with a light/camera source, or providing means for traction/countertraction during surgery. The dilation diameters of each of the access organs has been established as 20mm for the esophagus, 40mm for the anus, 9mm for the urethra, while the vagina has no well established maximum. Though many researchers have been looking towards using a single access point for natural orifice surgery, it appears likely that a dual-orifice NOTES procedure will provide a crutch for early-stage advancement of some interventions.

Access and closure to the peritoneal cavity in both open and laparoscopic surgery is fairly straightforward. An incision is made in the abdomen and enlarged for an open surgery, or a trocar is pushed through for laparoscopic procedures. As with laparoscopic procedures, insufflation is required, though maintenance and monitoring is difficult through a flexible endoscope. Bergstrom et al. is working on a method of more effective insufflation for new NOTES interventions. One researcher found natural orifice interventions to be very positive in the ability to work at low pneumoperitoneum pressures of only 5-6 mm/Hg. At the end of the procedure the wound is sutured or stapled closed. In either case, the location of the incisions can be optimized for each different intervention. Natural orifice surgery, however, does not have this luxury. Each case, no matter how different or complex, must start with the same access points:
stomach, colon, vagina, or bladder. Instead of moving a trocar by a few inches, the surgeon must now decide if is best to approach the procedure apical or basal. Additionally, closing the incision point is no longer an exercise for residents. Closing the internal wound is critical to the success of the surgery, technically difficult, and each access organ has specific challenges the surgeon must account for.

Some researchers are skeptical that any one or even two natural orifice cavities are currently suitable for safe NOTES procedures. Therefore, Pearl et al. propose a laparoscopic/natural orifice hybrid approach to be a natural stepping-stone for full acceptance of this new surgical technique. A hybrid approach will use natural orifice endoscopic surgery with a single laparoscopic visualization port. Another hybrid method uses the endoscope for visualization and the laparoscopic port for surgical interventions. As natural orifice surgery develops further, the hybrid approach will likely rely less on laparoscopic tools and more on endoscopic tools, eventually transitioning into a full NOTES procedure.

1.5.1 Transgastric NOTES

The most researched avenue for NOTES has been the transgastric route, likely because the social stigma associated with transcolonic, transvaginal, or transurethral approaches. A patient will be more accepting of a new procedure through the mouth rather than through the genitalia. The oral cavity for natural orifice surgery was the chosen access method for Dr. Anthony Kalloo when he first proposed the concept of NOTES in 2000. Gastric perforations are purposefully created for stomach bypass surgery and PEG tubes, so a precedent exists for this type of internal incision. Furthermore, the stomach is easily accessible and can be quickly rinsed meaning long preoperative fasting – as needed for a colonoscopy – is unnecessary. Transgastric natural orifice procedures are quickly becoming a focal point for NOTES development.
1.5.1.1 Transgastric Access

With the publication of Kalloo et al. transgastric peritonoscopy and liver biopsy in 2004, the field of modern NOTES was born, and transgastric pushed to the forefront of access techniques. One very large benefit of using the stomach is the ability for fast healing due to good vascularization and thick organ wall. Patients also agree that the gastric orifice would be the preferred method of natural orifice access. The gastric approach is best suited when the peritoneal intervention involves organs in the lower quadrant. This is because the endoscope maintains a relatively straight path from the mouth to the desired organ. If accessing the gall bladder, liver, or spleen, for example, the scope must undergo retroflexion after crossing the stomach wall. This creates difficulties for the surgeon who must push or pull on the endoscope opposite from standard procedures. In normal procedures, to get closer to the desired object, the surgeon advances the scope; to move away the scope is withdrawn. In the retroflexed position, the surgeon must pull the scope out in order to move closer the organ. See Figure 1-5 showing the difference between the straight and retroflexed endoscope position. Despite the surgical challenge of operating in the retroflexed position, many procedures have been pioneered in this manner. Overall, the gastric access point has allowed surgeons to take on many different types of procedures such as hysterectomy, oophorectomy, tubal ligation, resection of uterine horn, appendectomy, splenectomy, liver biopsy, lymphadenectomy, gastrojejunostomy, adhesiolysis, bowel anastomosis, and cholecystectomy.

![Figure 1-5: Difference between direct approach and retroflexion of an endoscope](image-url)
Before the incision is made through the gastric wall, the stomach must be cleaned of any contents to help reduce the risk of contaminants crossing into the peritoneal cavity. Kalloo et al. set this precedent by first cleaning and rinsing the oral cavity with Betadine. One has to remember this first experiment was performed on a porcine model, so an alternative to Betadine would need to be used in human experiments. The important fact here is the realization of researchers to clean the oral cavity in order to minimize the risk of bacterial infection. The mouth is an incredibly dirty environment harboring over 700 species of bacteria or phylotypes. The more common genera include *Gemella*, *Granulicatella*, *Streptococcus*, and, *Veillonella*. This risk and the necessity to reduce or eliminate oral bacteria have been discussed at both the 2006 and 2007 NOSCAR conference.

After the oral cavity is rinsed, the endoscope is advanced down to the stomach. En route the scope passes through the esophagus which can also harbor bacterial contaminants. To mitigate the risk here, the endoscope is placed inside an overtube designed to protect the external surface of the scope from coming in contact with the tissue. Once inside the stomach, the risk of bacterial contamination is reduced due to the inability for the stomach to harbor bacteria because of the incredibly low pH value – typically between three and four. However, spillage of these contents into the peritoneal cavity is recognized as a cause of sepsis, peritonitis, and in some cases death. Therefore the gastric contents are typically irrigated with clean water and some type of cleansing solution. In some cases, the antibiotic solution is left in the stomach for 10 minutes to insure proper cleanliness levels. This is similar to how the skin is prepared for open or laparoscopic procedures where the focus is on safe cleansing of the access area.

Crossing the gastric wall was first executed by using a needle knife to make an entrance site, then enlarging this hole large enough for an endoscope by using a pull-type sphincterotome. In almost all cases, the initial puncture wound is still made with a needle knife. The one innovation lies with the recognition that the initial blind needle knife puncture could potentially injure organs or tissue directly behind the gastric
tissue. To combat this issue, the proper selection of gastric anatomy – the anterior wall – helps to mitigate this problem. Additionally, Kalloo developed a novel endoscope attachment that allowed for the suction port of the scope to communicate with the much larger attachment, Figure 1-6. The result was that when the endoscope (1, 2) is pushed against the stomach wall (101), the suction is engaged and the gastric tissue is pulled into the attachment (20, 21, 22) and allowed for a nearly risk-free puncture. Whether or not this exact device is used, it seems as though some kind capturing technology may be needed to ensure safety to underlying anatomy.

![Figure 1-6: Patent application 2003/0225312 device to capture stomach tissue for safe organ puncture](image)

In addition to the original method of expanding the puncture site via sphincterotome, three more methods have been developed giving surgeons options to cross the gastric wall. The original Kalloo et al. gastrotomy used a pull-type sphincterotome to enlarge the needle knife puncture. A picture was taken during this procedure which shows the enlargement taking place, Figure 1-7. This technique is relatively safe and simple and creates a robust gastrotomy in which all superficial and muscular layers are impacted. This in turn allows repeated endoscope insertion, tissue manipulation, and organ retrieval. Though technically appealing for entry, the sphincterotome has an inherent risk or cutting a blood vessel making subsequent hemostasis a problem. Insufflation is difficult because the irregular gastrotomy edges do not seal well against the endoscope. Closure is also problematic because the floppy edges are difficult to pull together in a regular
fashion.\textsuperscript{87} True to many developing technologies, this early form of gastrotomy creating proved feasibility but more advanced techniques are now available.

![Image of gastrotomy](image)

Figure 1-7: Gastric incision being enlarged with a sphincterome\textsuperscript{34}

The second method of gastrotomy formation is common throughout many medical interventions – balloon dilation, or disruption. This method pioneered by Park et al. and Jagannath et al. involves using a radial dilation balloon. Shown pictorially in Figure 1-8, the balloon is inserted through the original puncture site, and inflated to 18mm – 20mm. Once fully inflated, the endoscope is snugged up to the balloon, and both are pushed through the gastrotomy site as one unit.\textsuperscript{72,90} Balloon expansion of the gastric wall is advantageous to the gastrotomy formation over electrosurgical expansion because it may be less traumatic to blood vessels thereby reducing the risk of bleeding. If bleeding does occur, the balloon can provide tamponade.\textsuperscript{87} In porcine experiments in 2005, Jagannath et al. proposed that due to the muscular nature of the stomach, sutures may not be needed since the gastrotomy site appears to spontaneously closed.\textsuperscript{73} However, necropsy revealed that while though the gastrotomy site appears closed, the thick muscular layer was gaping.\textsuperscript{87} This leaves a potential for slight leakage of stomach contents similar to a peptic ulcer. The conservative standard of care for peptic ulcers calls for urgent closure, and NOTES should follow suit with closure to eliminate any potential source of complications.\textsuperscript{91}
Both of the previously mentioned access techniques create a single congruent access point through the gastric wall that must be closed in order to reduce risk to patients. In 2007 a new method of crossing the gastric wall was pioneered. Self-approximating transluminal access technique (STAT) or submucosal flap safety valve (SMEF) uses the multi-layered stomach tissue to its great advantage. This method of access was formed not for ease of access, but for ease of closure and post-operative safety to the patient. Both STAT and SEMF are acronyms for the same style of procedure – creating a self-sealing flap during access to aid in closure. The onset of both procedures calls for a saline injection into the submucosal layer of the stomach tissue. SEMF then proceeds by using high pressure carbon dioxide to dissect the mucosal tissue from the muscular tissue of the stomach. A bleb of approximately 10cm can be created entirely from CO2 injection, however a urinary dilating balloon can also be used to dissect resistive connective tissue. This dissecting step is somewhat different in STAT, though both achieve the same result. Instead of a CO2 created bleb, the mucosa is dissected from the musculature by needle knife dissection under direct visualization. In both cases, a small access slit is cut into this bleb on one side, and an exit slit through the musculature is created on the opposite side. Surgery is carried on as usual. A pictorial of this technique can be seen in Figure 1-9.
This access technique was formed by approaching the NOTES surgery from a holistic approach instead of a systems approach. Instead of treating each part of the procedure separately, developers of STAT/SEMF chose to access the peritoneal cavity in such a way to facilitate faster, easier, and safer closing of the gastric defect. Of the two forms, neither has shown to be far superior to the other, though the author believes SEMF has a lower risk of bleeding complications over STAT from the use of needle knife dissection.

Finally, the last method of gastric access involves a hybrid procedure with that of placing percutaneous endoscopic gastrostomy, or PEG tubes. A needle is passed through the skin into the stomach and a loose suture left behind. This is done a second time a short distance away. A third puncture is made and an endoscope threads a guidewire through the tissue. A balloon is placed over the guidewire and inflated in the space between the stomach and the abdominal wall thereby creating the gastrostomy. Upon completion of surgery, the loose sutures are tied tight pulling the stomach wall to the abdominal wall creating a mechanical seal, Figure 1-10. This procedure seems like it may work well, but at the risk of permanently adhering the stomach to the inner abdominal wall where as
the STAT/SEMFT technique is self-contained. All, however, show a progression of the natural orifice procedures and an evolution into a clinically viable method of surgical interventions.

1.5.1.2 Transgastric Procedures

The gastric access site is perhaps the most researched of modern NOTES. Kalloo et al. introduced the world to purposefully crossing the gastric wall for peritoneal interventions. From there researchers began looking into developing procedures for a wide variety of organs such as: hysterectomy, oophorectomy, tubal ligation, resection of uterine horn, appendectomy, splenectomy, liver biopsy, lymphadenectomy, gastrojejunostomy, diaphragmatic pacing, and cholecystectomy. The stomach provides a convenient place to access the peritoneal cavity, but not all of these procedures are best suited for this access organ.
Cholecystectomy has received a great amount of attention from the NOTES community. The reason is perhaps to attempt to revolutionize a procedure that many patients need each year. A transgastric NOTES procedure for anatomy in the upper quadrants organs such as the gall bladder, spleen, kidney, liver, pancreas, or diaphragm require the surgeon to operate in the previously discussed retroflexed position. The retroflexed position offers many challenges to the physician that can easily be reduced or eliminated by operating in-line with the endoscopes currently available for natural orifice use.

Park et al. performed the first NOTES cholecystectomy in a porcine model in 2005. This study confirmed that a moderately complex natural orifice surgery in the retroflexed position is safe and viable. The time for each procedure ranged from 2.5 hours to 40 minutes, with time decreasing with each animal. All 8 animals survived the 22-days until necropsy; at which time they revealed well healed incisions and vascular clips held.73 Rolanda et al. also studied a transgastric cholecystectomy in the porcine model, however they used a transvesical access port for visualization in addition to the main transgastric port. With this dual access surgery, they realized the advantages of laparoscopy through the vesical port but without external incisions. The researchers were successful in all 7 pigs, and at necropsy the pigs did not show any signs of peritoneal soiling.75 Kantsevoy et al. performed a study on the feasibility of a transgastric spleenectomy.76 This procedure required the retroflexed position. The intervention was successfully performed despite the lack of specialized equipment for this style of procedure.

Given the current development of endoscopes available to a surgeon researching transgastric natural orifice surgery, it seems most prudent to avoid retroflexion and focus on procedures allowing a straight line between access site and target organ. This includes anatomy of the lower quadrants such as large and small intestine, colon, appendix, bladder, hernias, and internal female genitalia as prime surgical targets. Once the endoscope is passed through the stomach it is advanced directly to the organ without complex reorientation of the spatial field as occurs in the retroflexed position. The direct route allows the surgeon to more accurately manipulate the endoscope during surgery.
Transgastric access to the organs of the lower peritoneal cavity was pioneered by Rao et al. with their unpublished report of transgastric appendectomy in humans performed in India in 2003. Jagannath et al. in 2005 continued building upon the researchers’ previous work in natural orifice peritonoscopy, liver biopsy, and gastrojejunostomy. They reported successful transgastric ligation of fallopian tubes with long-term survivability. Six female pigs underwent the procedure, and all had very positive intraoperative and postoperative results. The anatomy was easily accessed and visualized. Post surgery all pigs ate well and gained weight, and upon necropsy there was no evidence of peritonitis or infections. Merrifield et al. also used NOTES as a method of female pelvic surgery – in this case a partial hysterectomy. Of the 5 pigs that underwent the transgastric hysterectomy, one did not survive the 14-day study period. Necropsy on day 4 revealed incomplete gastric incision peritonitis had formed. A second pig developed fever and at the end of this trial was found to have an abscess at the incision site and scattered abdominal pus. The other three animals survived without incident. Though this study showed the surgical feasibility of transgastric partial hysterectomy, it also showed the need for complete abdominal closure and attention to cleanliness during surgery. Wagh et al. also performed female pelvic interventions – oophorectomy and tubectomy – on 5 pigs. All surgeries and recoveries were uneventful. This uneventfulness of the study may be indicative of the short-term feasibility of such natural orifice surgeries performed on humans.

Besides surgeries in the female pelvic anatomy, another area of transgastric research lies with creating anastomosis. The creating of an anastomosis can be a quick and easy transgastric procedure because once the gastric wall is crossed, all that is left is to grasp the desired location of the intestine, pull into the stomach and connect the two. This procedure could be very important in bariatric surgery for Roux-en-Y bypass surgery as discussed earlier. The amount of time the stomach would be open to the peritoneal cavity would be very minimal, and NOTES could perhaps improve outcomes of such a surgery. Bergstrom et al. studied this concept in 12 pigs, 6 acute and 6 survival. The procedure was successful in all animals and the survival animals had no adverse
reactions. At a 7 day follow-up, an endoscope was passed through the anastomosis showing well healed tissue.\textsuperscript{103}

Eventually, the field of NOTES needs a multitasking platform optimized for this new surgery.\textsuperscript{104,105} One that has emerged is the Shapelock device developed by USGI, Figure 1-11(A).\textsuperscript{78,106,107} This device is used as a flexible overtube that can be stiffened once the desired position has been reached thereby providing a stable working platform, in addition to tool sterility. The Shapelock, unfortunately, has not gained widespread acceptance because it restricts valuable space to pass any standard endoscope through. Swanstrom et al. took the Shapelock design one step further by turning it into a full multi-tasking platform complete with one large diameter flexible optics channel, and two independently steerable working channels, Figure 1-11(B). This gives the physical more surgical options and allows the physician to triangulate during endoscopic procedures.\textsuperscript{78} Another overtube using balloons was developed by Hondo et al. This dual overtube design allows mostly sterile access to the peritoneal cavity, and the inner overtube incorporates a balloon which, once passed through the incision point, is pulled against the stomach wall and sealed, Figure 1-11(C).\textsuperscript{70} Though on the right track, tension must be kept on the inner overtube to ensure the balloon maintains its seal. To date there is not an adequate platform able to complete all the complex tasks that NOTES has the potential of tackling.

![Multitasking platform designs](image-url)
1.5.1.3 Transgastric Closure

When Kalloo et al. performed their first porcine transgastric peritinoscopy and liver biopsy, the gastrotomy was closed with endoscopic clips. When Jagannath et al. successfully pioneered balloon dilation of the gastrotomy in 2005, they did not seal the site at all. However, due to concerns about stomach contents potentially leaking into the peritoneal cavity, a consensus was reached that some type of active fixation must be used to help the gastrotomy site stay closed while the tissue heals. The importance of the gastric closure lead it to be one of the main issues discussed at the 2006 NOSCAR conference.

There have been several techniques suggested for closing the gastrotomy. The 2006 NOSCAR working group on this topic outline the following potential methods: clips, endoluminal suturing, T-fasteners, endoloops, nitinol umbrella, endoluminal linear stapler, tissue glues/sealants, energy source tissue sealants, prepositioned device, or perhaps a new technology not yet developed. Commercially available hemoclips have been used to close gastric defects following surgeries with moderate success. Kraft et al are developing a new over-the-scope nitinol clip which they are hoping is more secure than existing clips. Additionally, the clips remain difficult to use due to thickened mucosa from edema and hemorrhage from a long surgery. However, all of these clips are only able to close the thin mucosa and not the thick muscular layer. This may lead to problems healing because of the discontinuity of the muscles in the stomach, and one researcher to work on a method of closing the gastrotomy by using a series of three endoloops in the porcine model. Using instruments already available to surgeons, the physician was able to successfully close the gastrotomy in less time as it takes to place endoclips with equivalent success rates. On this same notion, Meireles et al. is working to evaluate the efficacy of using flexible endoscopic stapling devices to seal the gastrotomy. Preliminary studies are showing positive results, and long-term studies are under way to show healing characteristics.

One study attempted to quantitatively compare several gastrotomy closure techniques. Ryoo et al. compared three methods of closure and one negative control in an ex vivo
porcine stomach. A gastrotomy was formed with a needle knife puncture and 18mm balloon dilation. The site was subsequently closed with hand-sewn sutures (considered the gold-standard), endoscopic clips, and the LSI prototype access/closure tool, Figure 1-12. Since it is most likely for spillage of stomach contents to the peritoneal cavity to occur directly post surgery before any healing can take place, the ex vivo model is an adequate benchmark. The results of the study can be seen in Table 1-5.

![Figure 1-12: Distal portion of the LSI prototype](image)

<table>
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<tr>
<th></th>
<th>Number</th>
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<td>15</td>
<td>14-16</td>
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<tr>
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<td>5</td>
<td>47</td>
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<td>Clips</td>
<td>5</td>
<td>33</td>
<td>17-46</td>
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<tr>
<td>Prototypes</td>
<td>5</td>
<td>85</td>
<td>45-170</td>
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Table 1-5: Results of pressure testing different styles of closing a gastrotomy (in psi)

As already described, clips are not very adept to reliable closure of the gastrotomy and are only marginally better than the negative control. Hand-sewn closure was considerably better, while the prototype LSI tool performed the best. When leaks did occur, they happened through the site of fixation rather than in-between. The LSI tool was developed to safely access and close any intervention into the peritoneal cavity. It works by first selecting the access site and engaging the side port to suction. Then small needles are fired placing the sutures used to close the hole at the end of surgery. Finally, a small blade makes an incision through the tissue. The entire process is both fast and safe, two crucial factors for NOTES procedures.

Another device developed for full thickness suturing is the NDO Plicator. Initially developed as a treatment option for patients with GERD, it has now found its way into
the NOTES field. Shown in Figure 1-13, it works by grasping the full thickness of both sides of the defect, and suturing them together with small pads on each side for increased surface area. The mean time for closure is 15 minutes, however the suture pad may decrease visibility of the wound on follow-up procedures making accurate analysis of healing difficult.

Figure 1-13: Function of NDO plicator and resultant tab-closure

Two additional complex methods of closure were developed by Mellinger et al. and Kalloo et al. Mellinger’s g-Prox device which works in conjunction with the Shapelock device described earlier. A tool with distal graspers is pushed through the large working channel of the device. The graspers are able to grab an adjacent needle and rotate 45 degrees pushing the needle and thread through the tissue. The resultant fixation method is a pair of polyester tissue anchors able to simulate conventional suturing in remote areas of the body. The distal end of this device and the deployed anchor is shown in Figure 1-14.
The last complex suturing device is the Eagle Claw developed the Apollo Group in conjunction with Olympus. The device fits on the distal end of an endoscope, and the claw-like needles are able to take full-thickness bits of tissue and securely stitch them together. This device mitigates the difficulties of clip closures allowing full thickness closure while still using the “gold-standard” of surgical closure – the suture. Though a very interesting device, it must be loaded on the distal end of the endoscope independently just prior to closure, so clearly work must take place in order for this technology to be adopted.

A much simpler method of gastrotomy closure is done with the insertion of T-tags. These simple devices are merely a sharpened piece of metal or plastic on the end of a suture thread. Starting in-line with the suture, once punctured through the end tag turns and prohibits pulling back, seen in Figure 1-15. Several groups have experimented with various forms of T-tags with promising results. One of the largest advantages of this suturing method is its flexibility. Even very large gastrotomy sites with irregular or electrosurgically altered edges can easily be pulled together with like-tissues re-mating upon cinching closed.
Overall, the gastric approach has given some very useful information on the field of notes, but perhaps leaves even more questions unanswered. What is the ideal method of access the peritoneal cavity through the gastric route? Which procedures are best suited for this method of access? Should the focus be on attempting to replace current procedures, or using NOTES to tackle surgical interventions previously minimally invasive surgery can not perform, or even procedures that have not been realized yet? What is the best method of closing the gastrotomy? Though all of these questions must be answered before NOTES will become a reality in the operating room, one fact remains certain – transgastric natural orifice surgery is revolutionizing how the medical community is approaching both endoscopic interventions, and surgery in the peritoneal cavity.

1.5.2 Transcolonic NOTES

Though perhaps not accepted quite as mainstream as the transgastric approach, the transcolonic NOTES intervention is gaining popularity among researchers. First, the anal opening allows for larger diameter instrumentation than what can be passed through the esophagus. The straight angle-of-attack allows for both flexible and rigid instrumentation. Most importantly, the basal approach permits straightforward surgeries in the upper quadrants, eliminating the need for technically complex and surgically confusing endoscope retroflection. These benefits may seem to easily put the transcolonic approach superior to the transgastric approach for many upper quadrant surgeries; the colon is a much more delicate organ and worries about cleanliness before and after surgery have presented many technological challenges for researchers.
1.5.2.1 Transcolonic Access

Transcolonic natural orifice is very similar in many aspects to transgastric access previously discussed. However, the tissue of the colon is much thinner than and not nearly as muscular as the stomach. Because of this, the STAT/SEMF technique has not been attempted yet. Additionally, the tissue of the colon relaxes so readily after needle knife puncture that Fong et al. found balloon dilation to be unnecessary. Therefore, all that is necessary for transcolonic access to the peritoneal cavity is a small colotomy. This small colotomy typically is created via a needle knife incision. After the small incision is created, and endoscope can be pushed through the small opening over the needle knife cannula– the tissue relaxing as the scope is advanced. Despite the simplicity of access, several researchers are working on alternatives for colotomy formation.

A very slight variation was performed by Dubcenco et al. for transcolonic access to the peritoneal cavity. The organ was cleaned with several tap-water enemas and a balloon inserted and inflated in the colon higher than the desired access point. Pai et al. took this rinsing one step further by lavaging with a Betadine solution. The inflated balloon stops any remaining stool content from advancing down to the access site and immobilizes the colon preventing movement and rotation as seen in Figure 1-16. The colotomy site is subsequently created and expanded via needle knife. At necropsies, all 10 pigs showed no signs of peritonitis. Because the colon tissue is very pliable and relaxes easily, the incision site may become increasingly large during surgery – potentially allowing stool contents dislodged during surgery to soil the operating field. The balloon seals the access site from the rest of the colon increasing safety of the procedure.
Though merely a puncture-style colotomy creation, Wilhelm et al. is developing a method using transrectal ultrasound for a safer, more precise incision. As with gastrotomy creation, colotomy creation has a risk of injuring underlying anatomy. To mitigate this risk, Wilhelm first injects 1 L of taurolidin and 2.5 L of Ringer solution into the lower quadrant of the peritoneal cavity. The bowels subsequently float resulting in a safety area by separating the incision organ from other tissues. Next, an entry point is located with transrectal ultrasound and a purse-string suture tied around the entry point. A novel trocar is inserted through the center of the sutures and an endoscope passed through. The sutures keep the colon tight against the trocar allowing for insufflation. After surgery is complete, the sutures are tied. The most unique portion of this access is the recognition to set up colotomy closure at the initialization of surgery. The average procedure time was 9.3 minutes for access and 7.8 minutes for closure, however injection of the fluids took between 20 to 30 minutes. Post-operatively, four of the five pigs gained weight adequately, with the fifth animal delaying by two days with minor symptoms. This access technique shows promise, however further studies are needed to develop adequate statistical analysis.

Described above in the gastric access section, the LSI surgical device was evaluated by Fong et al. for transcolonic NOTES. It appears to work very well with the more flexible organ. Additionally, since the colon must be perforated to the side of the endoscope, this device lends itself particularly well to this application. The sutures placed at the beginning of the procedure also work to keep the colotomy site from expanding too large and create a better seal around the endoscope for enhanced pneuperitoneum.
additional device adapted to NOTES surgery is a transanal endoscopic microsurgical (TEM) platform originally developed for transanal microsurgery for full-thickness resection of rectal tumors, Figure 1-17. Due to the relatively short distance and straight route from the anal opening to colotomy site, transcolonic NOTES has the potential to allow rigid instruments. The TEM device allows multiple large diameter tools access to the colon and, in this embodiment, the peritoneal cavity. These two articles demonstrate the ability and necessity for NOTES researchers to find creative solutions from other areas of surgery.

When the gastric plane was crossed via balloon expansion, the stomach sealed fairly tight around the endoscope somewhat reducing the need for additional mechanical assistance. In the colon, however, the tissue behaves considerably different. The tissue relaxes during surgery potentially tearing and leaving a gaping discontinuity allowing stool to cross into the peritoneal cavity. Much of the effort above in access has focused on finding a way to keep the wound from becoming overly distended. Additionally, due to the polluted nature of the colon, sterility remains a surgical concern. Again similar to gastric access, though strides have been made, a clinically viable method of colotomy creation has yet to be developed.

1.5.2.2 Transcolonic Procedures

Surgical interventions using the anus as the access port is not a new concept. Surgery to remove intestinal polyps was reported in the 1970’s and early 1980’s by German
surgeons. In 1988 Dr. Buess completed a trial of 140 patients that underwent transanal microsurgery with only 7 complications. Currently, the anal opening is being heavily researched for NOTES procedures due to the large opening and direct access to anatomy of the upper quadrants. Predominantly being carried out in the porcine model, some of the procedures that have been tested are: full-thickness colon tissue resection, peritonoscopy, cholecystectomy, gastrectomy, and pancreatectomy.

Pai et al. pioneered transcolonic procedures by performing five survival cholecystectomies in a porcine model. Advancing the endoscope into the peritoneal cavity, full visualization of the peritoneal cavity was realized which included the liver, gallbladder, and spleen. This is in stark contrast to Wagh et al. whom were able to identify the gallbladder successfully in only 55% of the time. Figure 1-18 shows the direct route from the transcolonic access site to the upper peritoneal cavity. The cystic duct and artery were readily identified, exposed, and ligated with endoclip. Grasping forceps were used to pull the gallbladder away from the fossa and complete removal took an average of 68 minutes, though time decreased with increasing experience. The average time for the entire procedure from access to closure was 115 minutes. Four of the five animals had no adverse reactions and faired well, while the fifth animal was found to have incomplete colon closure and was euthanized 48 hours post surgery for concerns of peritonitis – which necropsy confirmed. Though the outcomes of this study were only moderately successive with a 20% complication rate, the ease of upper quadrant anatomy identification served to reinforce the theory that a single access route for NOTES is unlikely and the access organ may need to be adjusted for optimal surgical technique and outcome.
Ryou et al. had similarly positive results with the transcolonic access, though the surgery performed was a pancreatectomy. In this study, both the colon and vagina were used as NOTES access organs. During surgery each access site was able to complement the other to allow the surgeon triangulation during the procedure. All five pigs had excellent exposure of the pancreas, and the two survival animals recovered without incident. The mean procedure time was only 57 minutes. The authors disclose one very important disclaimer about this procedure: the transcolonic pancreatectomy is much easier in the porcine model than in humans; large vessels do not need to be dissected and the splenic vessels must be specifically targeted for preservation. Additionally, Ryou et al. recognize that this procedure was performed on healthy animals. Diseased animals and organs would pose an additional difficulty as vascular structure would be increased and small-vessel dissection would be necessary. Mintz et al. also performed a dual-orifice approach by removing a portion of the stomach successfully of five pigs transcolonically with transgastric support. This was not a survival study, however, but the authors had success in creating a gastric pouch and removing the remnants through the anal opening. Despite the successful procedure, the researchers highlighted the need for extra-long tools for the surgery – yet another cry for NOTES specific tools.
Though not technically a full NOTES procedure, Rajan et al. performed full-thickness colon resection in a porcine model. The reason for mentioning this here is the procedure calls for full-thickness sampling of the colon wall – which leaves a temporary anastomosis between the colon and the peritoneal cavity. This study showed positive results in their method, giving more supporting information for the acceptance of purposefully creating a discontinuity in the colon.

The list of current NOTES procedures via the colon is relatively short. This access point has been slow to catch on compared to the initial enthusiasm involved with the stomach. Even still, it seems as though the physicians are recognizing the benefit of interventions into the upper quadrants from the anal opening. The straight route for interventions through the colon make identifying and working on organs such as the gall bladder, spleen, stomach, and pancreas much simpler than operating in the retroflexed position.

1.5.2.3 Transcolonic Closure

 Whereas the gastrotomy site had initial supporters believing the site did not need active closure, researchers on transcolonic NOTES have fully realized the necessity to close this wound. The stomach has a very muscular wall that at least partially closes spontaneously after balloon-dilation; the colon is a much thinner, more delicate organ that tends to relax during surgery rather than contract. This leaves difficulties in simply capturing the two opposing sides of the colotomy as they may be a considerable distance apart. One simple method involves merely placing sutures at the onset of surgery to eliminate the technical challenge of grasping tissue after the procedure. Even still, many techniques have been used, some similar to gastrotomy closure while others are novel to the colon.

A device already discussed in gastrotomy closure has received more attention on the distal portion of the gastrointestinal tract: the LSI access and closure device. The graphical description of the device can be seen below. As can be seen in Figure 1-19, the LSI is designed to access organs perpendicular to the device. Also, it uses suction to hold the tissue in place, and the colon has thin tissue easily manipulated via suction.
Since this is the method of access used in the colon, this device appears particularly adept to transcolonic NOTES. During use of this device, very fast access and closure times were recorded. Fong et al reported full closure in less than 2 minutes.\textsuperscript{123} From this device it seems as though there may be a trend leaning towards combination access/closure devices with a focus on reduced procedure time.

Figure 1-19: (A) Device tip before capture (hollow chamber), (B) Parallel needles advance (through tissue), (C) Needles engage distal ferrules attached to either end of single suture, (D) Central blades fires to create incision, (E) Needles retract, deploying suture in process, (F) Purse-string suture fully deployed, (G) Guidewire insertion through incision.\textsuperscript{123}

The use of t-tags as colotomy closure likely stemmed from the innovative use of such devices for gastrotomy closure.\textsuperscript{102} A pictorial description of the technology is shown below in Figure 1-20.\textsuperscript{134} A needle catheter is loaded with a metal tag with suture thread attached. The needle is punctured through the organ wall, and when retracted the metal tag stays behind trailing the thread. A second is placed in the tissue directly opposing the first, and they are fastened together by pushing a thread locking/cutting device down the threads until the tissue meets. With this style of closure, nearly any size or shape of
perforation can be closed as evidenced by Raju et al. who successfully closed colon perforations in which 3 of 4 were gaping with everted edges.\textsuperscript{108} Ryou et al. and Sporn et al. also achieved very successful outcomes of colotomy closure with T-tags.\textsuperscript{131,135} All of the t-tag trials reported no major clinical complications post-operatively. The simplicity and versatility make this closure style appear very likely to remain in the spotlight of closure research.

![Figure 1-20: Colon suturing using T-tag method\textsuperscript{134}](image)

Also similar to stomach closure, endoscopic clips and endoloops have been explored as a method of colotomy closure.\textsuperscript{123,124,131,136,137,138} Whereas these tools were not entirely effective due to the thickness of the stomach’s muscular layer, the colon seems a better fit for the thin colon and has been used in isolated emergency closure of colon perforations.\textsuperscript{139} However, while Fong et al. and Ryou et al. realized very good results with endoloops and endoscopic clips, the success rate Pai et al. achieved was only 80%. The problem of complete closure remained despite the more ideal tissue as endoscopic clips and endoloops are primarily designed for achieving hemostasis.\textsuperscript{124}

Despite these endoscopic clip uncertainties, the concept is still being developed by some researchers. One such tool to use endoscopic clips is the Multi-Clip Applier under development by Ethicon Endo-Surgery. This clip device is unique, however, in that it can
fire up to four clips with a single insertion eliminating the need to remove and reload the device. The distal end is also rotatable allowing the physician to more accurately place each clip, shown in Figure 1-21. Upon initial porcine trials, the device has worked quite well with success in 12 of 13 animals in one trial, and though a variety of minor complications were found in a second trial, 5 of 6 animals were successfully closed.\textsuperscript{108} The most important benefit is reduced surgical time with median time to place 2 or 4 clips being just 2 or 3 minutes respectively.\textsuperscript{138} The major problem with this device is similar to traditional endoscopic clips – the inability to successfully grasp opposing tissue from a gaping wound. Comparing those tissues that were successfully closed with the Multi-Clip Applier to closure with suture closure via t-tags, the results are nearly identical, as seen in Figure 1-22.\textsuperscript{134}

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{figure1-21.png}
\caption{Figure 1-21: Multi-Clip Applier in development by Ethicon Endo-surgery\textsuperscript{138}}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{figure1-22.png}
\caption{Figure 1-22: Fully healed colon wall (internal and external) after closure with Multi-Clip Applier\textsuperscript{134}}
\end{figure}
The final method of colotomy closure is the novel suturing device also discussed earlier – the Eagle Claw. Fitting on the end of a standard endoscope, the device allows the user the ease of familiarity with standard navigation. Different from other devices that attempt to simulate sutures, the Eagle Claw uses fixed suture to fix opposing tissues. It is similar to endoscopic clips in that it must be removed and reloaded with a single suture each time it is used. The device, seen in Figure 1-23, has had mixed results. Though full-thickness suturing was achieved in eight of ten pigs by Pham et al. two were euthanized immediately because closure was not achieved.\textsuperscript{140} In one of these, the jaws of the Eagle Claw were not fully collapsed when it was retracted resulting in a defect of over 6 cm leading to severe pneumoperitoneum and hemodynamic instability. The second animal had an initial suture placement which blocked viewing of subsequent placements. Also, following the intervention but before closure, the endoscope must be removed to attach the device leaving the peritoneal cavity open to the colon for a brief period of time. On the positive side, the seven animals that completed the study were found to have well healed colotomies showing full-thickness reconstruction.

\textbf{Figure 1-23: View of distal end of Eagle Claw endoscopic suturing prototype\textsuperscript{140}}

These issues discovered during the initial animal trial of the Eagle Claw highlight the potential safety issues when developing methods of colotomy closure. The resultant technology must maintain safety to the patient even in the event of operator error. Endloops and endoscopic clips are appealing to many because surgeons are already well-versed at this technology, however the results are less than perfect – as much of these tools were not optimized for this task. The novel clips, T-tags, and suturing devices are
working towards the right direction but optimization is necessary to create a device optimized for NOTES full-thickness closure. From the sheer number of different styles and devices created for colotomy closure after a NOTES intervention, it is clear this issue remains high on the needs list for future innovation.

1.5.3 Transvaginal NOTES

Transvaginal NOTES is the earliest form of any natural orifice surgery. As previously noted, the first natural orifice intervention via the vagina was a culdoscopy performed in 1901 by Dr. Von Ott (Von Ott). This method of peritoneal interventions for females continued expanding through the next several decades. It became readily accepted in the 1940’s, and in 1975 culdoscopy was first performed using only local anesthetic.12,13 However, all cases prior to the 2007 report of the first transvaginal cholecystectomy were performed before the most recent advent of NOTES.

1.5.3.1 Transvaginal Access

Unlike the first two access methods, the vagina has not had any specialized attention given to access. During the culdoscopy procedures of the past, the procedure begins with a puncture with a trocar similar to laparoscopic procedures.22 The natural orifice procedures begin like transgastric and transcolonic with a cleansing of the external orifice with a 10% povidone-iodine scrub. After inspection to find the optimal insertion position, the puncture is made with a needle-knife, after which the endoscope is advanced directly into the peritoneal cavity.131 In some cases, an 18mm dilation balloon is used to dilate the incision to allow the scope easier access.

Crossing the vaginal wall has not been nearly as researched as the gastric or colonic access ports. Whereas both the stomach and colon are very dirty organs and have digestive contents that are harmful to the peritoneal cavity, the vagina does not have materials consistently moving through it on a daily basis. Additionally, like the colon, access through the vagina is relatively close to external orifice access. This allows the surgeon to explore many different options as both rigid and flexible tools could be used.
Though the vagina can only be used in approximately 50% of the population, it has advantages of the colonic access to the upper peritoneal cavity without the possible fecal contaminants.

### 1.5.3.2 Transvaginal Procedures

The full potential of transvaginal procedures has yet to be even remotely fully realized. To date there have been very few transvaginal NOTES procedures, however the vagina has been used for some time as a method of organ removal following laparoscopic interventions. Tsin et al. used the vagina to remove the gall bladder in 2001.\(^{22}\) In fact, as early as 1949 an appendectomy was performed during what was supposed to only be a vaginal hysterectomy.\(^{141}\) The organs removed through the vagina during laparoscopy include the gall bladder, colon, spleen, and kidney.\(^{142,143,144,145}\) The modern NOTES procedures that have been performed through the vagina are similar to the transcolonic approach, targeting organs of the upper peritoneal cavity. This seems most logical given the straight angle for surgery which eliminates the need for retroflexing the endoscope. These procedures are comprised of cholecystectomy, pancreatectomy, and appendectomy – with the cholecystectomy being the main focus.\(^{23,131,146}\) The relative lack of procedures may be because only half the population is able to have this procedure. Even still, the transvaginal approach offers a very unique route to the peritoneal cavity that no other orifice provides: complete lack of daily digestive contents or waste materials.

The first modern transvaginal NOTES procedure was the cholecystectomy. As already stated, the direct access makes this an enticing procedure from this access organ. The first human case was reported by Zorron et al. in March 2007 at the University Hospital Teresopolis in Brazil.\(^{67}\) In this elective case, a 43-year-old woman underwent surgery which took 66 minutes. During this procedure, a 2-channel videocolonoscope was used for the major functions of the procedure, and a 3mm laparoscope was inserted into the right upper quadrant for gallbladder retraction during dissection. The patient recovered very well post-operatively and was discharged within 48 hours without complications – and without any postoperative pain medication. The remarkable speed and efficacy the
physicians were able to perform this operation in was likely due to their previous 14 months of experimental work on porcine animal models.

The next several published papers on transvaginal natural orifice surgery are also described as hybrid approaches either with laparoscopic assistance or dual-orifice access. Similar to the procedures by Zorron and colleagues, Bessler et al. performed transvaginal laparoscopically assisted natural orifice surgery on a 66-year-old woman. A slight modification to the hybrid approach was used by Ryou et al. who used dual-natural orifice access points for increased surgical triangulation and visualization. In the porcine model, they used two endoscopes for the pancreatectomy – one transcolonic, and one transvaginal. They reported successful outcomes and the transvaginal scope complimented the transcolonic scope both during the procedure and closing the colon defect.

In an unpublished report, Dr. Horgan and Dr. Talamini of UC San Diego Medical Center announced the successful removal of the appendix using surgical techniques completely through the vaginal opening, though a 2mm incision was made through the belly button to aid in access. This 50-minute procedure marks a first in complete surgical interventions solely transvaginally with the use of novel laparoscopic instruments with multiple degrees of freedom and tactile feedback – thereby actually skirting the use of an actual endoscope.

Taking the surgery one step further, Marescaux et al. performed a successful cholecystectomy in a 30-year-old woman entirely transvaginally. Again a 2mm port was placed through the belly button for insufflation and monitoring of pneumoperitoneum. An endoscope was used for the entirety of the procedure. Following the 3 hour procedure, the patient recovered quickly with no pain. Despite her feeling well, she was kept overnight for monitoring since this was the physicians first case. At the 10-day follow-up the patient had resumed full activity without any discharge, bleeding or discomfort. This operation shows the unique ability for such procedures to radically change not only the surgical procedure, the patient experience during recovery.
Though the research into transvaginal procedures is not nearly as full as transgastric or colonic procedures, the outcomes have been very promising. It allows surgeons to decide whether an endoscope or laparoscope will suite the intervention best. Complete lack of post-operative pain makes the transvaginal all the more appealing for half the population. It seems as though as the different forms of natural orifice progress, the divisions will become blurred and surgeons will become more willing to specialize the access organ with the surgical procedure.

### 1.5.3.3 Transvaginal Closure

Closure of the vaginal otomy is extremely different than the gastrotomy or colotomy. Zorron et al. believe closure of the vagina is not as problematic of issue as the other natural orifices.\(^6^7\) The vagina has a long history of interventions by gynecologists performing transvaginal hysterectomies which has shown safety with respect to closure and infections.\(^1^4^6,1^4^9,1^5^0\) In these procedures there has been an extremely low risk or infection or hernias – even if the incision is not completely closed. This is shown by many gynecologists who neglect to even close the incision following pelvic surgery. For those who wish to close the incision, the vagina is routinely closed using standard surgical techniques.\(^1^4^7\) This is likely because the other three orifices must stretch, conform, and allow passage of food, stool, and urine – all hazardous materials in the peritoneal cavity. A leak from any of these organs could render severe clinical manifestations. The vagina, however, is considerably more static and does not pass materials on a daily basis, and has. Building on the standard practice for gynecologists to not emphasize vaginal closure, NOTES researchers are cautiously optimistic for similar results. So far the results are promising.\(^6^7,1^3^1,1^4^7\) Though validation through experimentation must accompany the vaginal closure theory for the considerably more invasive procedures that NOTES can offer.

### 1.5.4 Transvesical NOTES

Like the transvaginal natural orifice, the transvesical approach also has a very long history of interventions that have mostly gone unrecognized to the NOTES community.
Starting in the late 1920’s to early 1930’s surgeons began transurethral prostate surgery.\textsuperscript{10} Despite this long history, very few modern natural orifice surgeries have used the transvesical method. However, a major benefit to transvesical parallels that of the other basal approaches – direct access to the upper quadrants of the peritoneal cavity. This access method has major size limitations, however, which may relegate it primarily to a supporting triangulation role during surgery.

1.5.4.1 Transvesical Access

The method of peritoneal cavity access through the bladder is quite similar to access through other natural orifices. Lima et al. describe their methods in one of the first publications on natural orifice transvesical procedures. The first step to access is universal across the board – rinsing and perhaps lavaging the organ. The bladder was emptied and refilled with saline before making an incision in the organ wall with a surgical scissors introduced through the working channel of a ureteroscope. Next, a 5 Fr urethral catheter was advanced through the incision to provide access to the peritoneal cavity. A guidewire was then passed through and a dilator of a ureteroscope sheath enveloped by a flexible over tube expanded the incision to 7 mm. The ureteroscope was then inserted through the sheath allowing access to the peritoneal cavity while minimizing the amount of muscular disruption.\textsuperscript{151} This same procedure was used by Rolanda et al. in their combined transcolonic and transvesical interventions.

1.5.4.2 Transvesical Procedures

Similar how culdoscopy was developed and used before NOTES was coined, so too was the TURP procedure. The earliest use of the vesical access route was in urology for Transurethral Resection of the Prostate (TURP). TURP is a procedure to treat moderate to severe Benign Prostate Hyperplasia (BPH), a common clinical problem in which the enlarged prostate partially blocks the urethra in aging males.\textsuperscript{152} The first transurethral operation for an obstructed bladder was described in the 16\textsuperscript{th} century.\textsuperscript{10} In the more modern procedure, a rectoscope is inserted through the urethra into the bladder where the surgeon then accesses the prostate and removes targeted internal sections.\textsuperscript{10} This
transluminal intervention is perhaps the oldest transluminal procedure, however the last to catch with modern NOTES.

After NOTES became more popular with Dr. Kalloo publishing the first account of transgastric surgery, other natural orifices were explored as well. Whereas the gastrotomy has a difficulty in reaching the organs of the upper quadrant, they are easily reached via transvesical. The straight line of sight allows the use of standard urologic instruments, both rigid and flexible. The largest downside to transvesical procedures is the very limited size of passable instruments. As stated earlier, the typical maximum scope used by urologists is 9 mm. This means procedures using only the transvesical approach would be unlikely. Instead, this port could be used in conjunction with another natural orifice for visualization or for traction/countertraction of tissues. Rolanda et al. used the transvesical port for grasping and manipulating the gall bladder combined with a transgastric cholecystectomy. The additional manipulation proved quite valuable in this procedure because the transgastric cholecystectomy is especially difficult due to endoscope retroflexion. Furthermore, the vesical port allowed the physicians to work under controlled pneumoperitoneum – something the gastroscope alone will not facilitate. The results of the procedure were positive and highlighted the usefulness of the dual-port NOTES procedure.

In the case where a surgical assessment of the peritoneal cavity must be performed, the transvesical approach is by far the least invasive access method. Lima et al. disclosed their study of 3 acute and 5 survival pigs of a transvesical peritonoscopy. Using the access methods above, they successfully navigated and explored the peritoneal cavity. All animals recovered without incident and necropsy did not reveal any clinical complications. Urologists are seated quite well for transition into the NOTES area as they are trained in peritoneal cavity anatomy and surgical techniques in the event that complications must be handled immediately. Additionally, with the difficulty some researchers are having with closing the stomach or colon, it is possible that the urologist may be vital in closure from within the peritoneal cavity. Though the transvesical procedures may be limited to exploratory or supporting roles, the usefulness of such
procedures has already been shown to dramatically enhance the physicians’ surgical experience.

1.5.4.3 Transvesical Closure

Following TURP procedures, the bladder wall is actually not mechanically closed. Instead, a catheter is placed through the urethra to keep the bladder from expanding thereby allowing quicker healing. The transvesical NOTES procedures are approaching the closure issue similar to early transgastric procedures – lack of active fixation. The bladder wall is similar to the stomach wall in its muscular nature, and Lima et al. noticed the perforation seemed to spontaneously contract after the catheter was removed. Since the access was balloon dilated, much of the muscular layers were kept intact which helped this process take place. Additionally, bladder decompression using a urinary catheter was used to keep the pressure of the bladder down to allow quicker healing.\textsuperscript{151} Despite urinary leakage into the peritoneal cavity following a bladder perforation is associated with peritonitis or pathological bladder conditions such as neoplasms, NOTES applications have not encountered this yet.\textsuperscript{154} Early transgastric procedures also had similar successes, but the risks were decidedly not worth the rewards and active fixation is now preferred. Through the evolution of more and more invasive transvesical procedures this same evolution will likely occur.

The purpose of discussing the transvesical approach was for completeness in describing the breadth to which natural orifice surgery has spread. Surgeons are striving to push the envelope of minimally invasive surgery for the betterment of patient outcomes and patient care. This applies also to natural orifice surgery. Through a very small opening, the benefits could potentially make the transvesical opening an important supporting role in complex interventions. The ability to use the port either as a camera, or for traction/countertraction would be very valuable if a different organ was compromised for some reason. Even still, as the work presented in the rest of this document pertains to endoscopic technology, the use of the transvesical opening will not be considered as it is much too small for the current state of the work.
1.6 Patent Review

Since this is a project-based research project, a thorough patent and patent application search must be performed in order to ensure the anticipated devices do not interfere with the prior art. Everything from device to method patents can be found on the subject. The general concept can be seen in Figure 6-1 from patent application 2007_0163585. When looking for patents, some of the main keywords used for the search were: endoscope, endoscopy, natural orifice, NOTES, needle knife, overtube, guidetube, airway, flexible, balloon, dual balloon, dilation, catheter, electrosurgical, cautery, and surgical fastener.

![Figure 1-24: Typical surgical setup needed for a NOTES procedure](image)

1.6.1 Overtube Patents

Overtubes are an aspect of natural orifice surgery in which the endoscope is pushed through an additional tube to aid in cleanliness and reduce trauma to surrounding tissues. There are a wide variety of overtubes and guidetubes each slightly different for their main target. The overtube which is discussed throughout this paper provides sterility as its foremost function and therefore mechanically stabilization of the endoscope is of no concern; devices which provide stability could be used in conjunction.
Overtubes can be very simple or quite complex in nature. Some examples can be found in patents 5,259,366 – (A)\textsuperscript{156} 6,535,764,\textsuperscript{157} or patent application 2007/0167676 – (B),\textsuperscript{158} and 2007/0167675 – (C),\textsuperscript{159} as shown in Figure 1-25. Patent 5,259,366 merely works as a clip-on attachment on the endoscope giving it more working channels, so it actually would not help much in sterility. Sterility is of chief concern with the very simple tube used in patent 6,535,764. A second solution is to make an overtube designed to facilitate ease of creating and closing the otomy as 2007/0167676 has. Basically, this is a simple endoscope with a very large working channel allowing a standard scope to travel down the length while smaller working channels lie in the outer wall to facilitate otomy closure. In a very broad sense, this is the general concept behind the sterile access conduit, however this design is incredibly simplistic and lacks the multi-functionality that NOTES needs.

![Figure 1-25: Three overtubes used in NOTES interventions\textsuperscript{156,158,159}](image)

Not all guidetubes are meant to pass the entire way to the stomach. Since the majority of the bacteria are contained in the oral cavity, simple devices such as patents 4,807,593 – (A)\textsuperscript{160} and 5,620,408\textsuperscript{161} work to reduce some bacterial contamination. However, stomach contents are still free to interact with the endoscope if the surgeon is not careful. This is overcome with patent application 2007/0255165 – (B).\textsuperscript{162} This simple overtube enters through the stomach and passes all the way into the peritoneal cavity. A bit more complex is patent application 2007/0260214 – (C).\textsuperscript{163} This overtube is large enough to allow three small steerable endoscopes to pass through thereby allowing the surgeon the
ability to grasp tissue while cutting or maneuvering inside the peritoneal cavity. These patents can be seen in Figure 1-26.

Three more interesting styles of overtubes are seen in Figure 1-27 from patent applications 2007/0198000 – (A), 2006/0237023 – (B), and 2004/0186350 – (C). Application 2007/0198000 is interesting as the inventors are using an external magnet which interacts with magnets in the endoscope to aid in maneuvering. 2006_0237023 is interesting in that the overtube has several very small lumens built into the external wall which are used to place surgical fasteners to facilitate closure. The functionality and ability for a device to anticipate closure at the beginning of surgery is unique to NOTES interventions. Finally, patent application 2004/0186350 provides the ability for the overtube to be flexed, then locked into the desired position providing a stable platform for an endoscope to work from.

Another common theme to overtubes is the use of balloons for a variety of purposes. The flexible overtube will have dual balloons on this flexible membrane to dilate and clamp the access organ. Both single and dual balloons have been used extensively to assist in
anchoring during surgery. Figure 1-28 shows several balloons used in a similar fashion. Patent 7235064 – (A)\textsuperscript{167} describes a dual-balloon system for anchoring during laparoscopic surgery. In such a system, the trocar would not inadvertently back out of the hole in cases where the patient is quite large with thick fatty layers. Balloons and dual-balloons are also used to assist in anchoring endotracheal tubes as in patents 4091816\textsuperscript{168} and 4688568 – (B).\textsuperscript{169} Balloons to block the flow of liquids are also used in both the upper and lower gastrointestinal tract, and urinary systems as in patents 2007/0265600,\textsuperscript{170} 7264609,\textsuperscript{171} and 4932958 – (C).\textsuperscript{172}

![Figure 1-28: Overtubes used for various endoscopic procedures](image)

More closely resembling the goals for this research are patent applications seen in Figure 1-29, 2007/0142706,\textsuperscript{173} 2007/0167967 – (A),\textsuperscript{174} 2007/0203517 – (B),\textsuperscript{175} and 2008/0119868 – (C).\textsuperscript{176} The overtube in patent application 2007/0142706 is meant as a quasi-stable platform after the balloon is inflated in the operating lumen. Patent application 2007/0167967 uses dual balloons to keep the stomach separated from the interior abdominal wall so it becomes easier for an endoscope to pass through this area. The final two overtubes behave in a very similar fashion; both 2007/0203517 and 2008/0119868 use dual toroidal balloons upon access to the peritoneal cavity. 2007/0203517 uses a very long tube meant to access through the mouth and the balloons clamp the gastric tissue. This provides a means to access the peritoneal cavity without contamination or spillage of stomach contents. Patent application 2008/0119868 does the same thing except it is much shorter and crosses the vagina.
1.6.2 Needle Knife and Surgical Fastener Patents

Two more areas of patents that were looked into involve needle knives and surgical fasteners. Both of these areas of research have a very long history of patents going back to the 1960’s. In this application, a needle knife is merely a method of electrosurgery to gain access to the peritoneal cavity. This concept can be traced to patent 3,768,482 in which a voltage was applied to a knife to help facilitate cautery.\textsuperscript{177} This evolved into a very simple device in patent 5,536,248 in which a thin wire is given a positive electric charge.\textsuperscript{178} The circuit is complete with a negative-terminal patch placed on the skin elsewhere. The small area of voltage on the positive terminal electrically cuts and cauterizes the immediate tissue. Since this was patented in 1995, the time limitation has run out and its technology can be used in other applications without legal ramifications.

For the proposed devices, the surgical fastener style to be used is called a T-tag, two examples are shown in Figure 1-30. This style of fastener has a T-shaped device in which the top the “T” can be rotated inline to ease placement. Like a toggle-bolt, once the “T” has punctured tissue, the top rotates back out and can not pass back through the puncture site. Many different varieties of T-tags have been patented; the first being 3103666.\textsuperscript{179} This application involves placing a one-piece T-tag into clothing for attaching clothes. There is little difference between attaching a tag to clothes or two pieces of tissue together. With tissue, however, the two layers must not be allowed to have variable
distance apart and rather need to be actively held together. Patent 4,006,747 – (A) uses a one-piece fastener for tissue but overcomes potential gaping tissue with the way the fasteners are inserted.\textsuperscript{180} They are placed across tissue at a distance away from the incision so when the tissue relaxes the T-tags are pulled tight while still allowing tissue to heal. This style of surgical fastener has been used extensively, and recently was modified slightly to allow two T-tags to be inserted through the same working channel of an endoscope. Patent application 2007/0191886 – (B) shows this new method along with T-tags with a long piece of suture thread attached so the surgeon can place these fasteners and secure tissue in hard-to-reach places.\textsuperscript{181}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{image1.png}
\caption{Two methods of T-tag insertion for active fixation of two layers of tissue\textsuperscript{180,181}}
\end{figure}

Clearly, there is a long history of intellectual property on many of the embodiments of the proposed device. Understanding the extent of the current IP is crucial to ensure none of the devices conflict, and if they do find a different solution around these limitations. Every part of the device has prior art associated with it. Though IP exists on each of these, there exists a seam in connecting many styles of technology already in use with several new ideas to form a new method of gaining access to the peritoneal cavity for natural orifice surgery.
1.7 Problem Formulation

After reviewing the academic literature and technical intellectual property it was determined that there exists a clear gap the ability to access the peritoneal cavity in such a manner to virtually eliminate the risk of infection to that of laparoscopic surgeries. The proposed method to reduce infections involves a novel overtube-like device, shown in Figure 1-31 which will allow for the endoscope to be passed through the access organ down to the peritoneum in a sterile manner. It will be passed through the endoscope channel positioned at the appropriate position in the stomach. Suction will then be used to create traction on the organ wall, allowing for safer creation of a gastrotomy – via an incorporated needleknife – by pulling the gastric wall away from organs outside the stomach which could potentially be injured. A two-part dilation balloon is then inserted through the hole. The balloons dilate and seal the hole using distal and proximal “donut” balloons effectively holding the conduit in position. The endoscope is subsequently removed and the sheath is left behind. A second sterile endoscope is then introduced through the conduit into the peritoneal cavity to perform various surgical procedures. Once in place, this device provides a completely sterile conduit to access the peritoneum. When surgery is complete, the endoscope is removed and the “donut” balloons are deflated and removed, leaving behind only the T-tags to close the gastrotomy.

![Figure 1-31: Delivered balloon-assisted endoscopic sheath](image)
1.8 Overview

Natural orifice surgery is a radically new form of minimally invasive surgery that is poised to drastically change the surgical experience. NOTES involves performing surgical procedures with a flexible endoscope through a natural orifice such as the mouth, rectum, urethra, or vagina. It removes the need to create incision across the abdominal wall thus minimizing or even eliminating post-operative pain, abdominal scars, and complications such as incisional hernias and adhesions.

Of the four orifices used in NOTES surgeries, only three are major access organs capable of performing complex surgeries with an endoscope capable of resecting whole organs: stomach, colon, vagina. Perhaps due to the lack of social stigma, the transgastric NOTES approach has been the most popular avenue for surgeons transferring into natural orifice research. The stomach is well suited to these interventions for several reasons. There already exists a surgical precedent in gastric bypass surgery of opening the stomach in the peritoneal cavity and resealing the holes created. The risks have been well mapped, and methods produced to successfully cross and seal the gastric wall with minimal infection or leakage rates. However, until a stable surgical platform specifically designed for natural orifice surgeries is developed, the transgastric approach lends itself best to operations in the lower peritoneal or pelvic regions. This eliminates the need to retroflex the endoscope which can cause the surgeon confusion. Regardless, physicians currently spend a great deal of time and effort to minimize the risk of infections when introducing endoscope to the peritonea cavity by means of the mouth.

The other two access organs lend themselves best to interventions in the upper peritoneal regions, or organs directly viewable in the pelvic region. Used for decades with a very high success rate, a female culdoscopy is a form of natural orifice surgery and provides the groundwork for further interventions. The colon is considerably dirtier than the previous two organs discussed. Even still, it provides a clear view of the upper quadrants in the entire population. A great deal of effort has been exerted by colorectal surgeons who use NOTES procedures to reduce the risk of peritoneal soiling from stool contents. Once again, a need has been shown for reduced or eliminated infection and leakage risks.
A review of the currently available surgical tools, prototype tools, and even patents and patent applications demonstrates clear need for a device or system specifically designed for natural orifice surgery to simplify and increase patient safety for crossing the gastric tissue. Doing such would greatly shorten the preparatory time and closure time surgeons currently must take. The device proposed in this paper will work as a completely sterile natural orifice access device. The patient is at a lower risk of intra-operative and post-operative complications, and the entire process is simplified for the surgeon.

A review of the literature has shown a clear gap in technology for a sterile surgical conduit for natural orifice surgeries. This device is needed for natural orifice surgery to make the move from research and trials to widespread clinical acceptance. The ability for surgeons to gain access to and perform operations in the peritoneal cavity safely using the proposed device has the potential to revolutionize surgeries worldwide.

### 2. Material Properties

#### Introduction

Material properties are one of the most important sets of data used when performing any kind of FEA study. The results from a FEA simulation are only as good as the assumptions and data input. When working with biological materials, the tissue properties can be the most important assumption. This chapter discusses the work pertaining to obtaining a material model for human gastric tissue. Finding an accurate model of the human gastric tissue in the literature was virtually non-existent, therefore tissue was pull-tested to obtain accurate first-hand tissue properties. This data was analyzed and compared to known materials for subsequent use in experimental procedures. Finally, the new material model was loaded into the FEA simulation for iterative device/tissue interface testing.
2.1 Background

It has been realized that material properties “have been shown to directly influence, and in some cases, control the dynamic interactions that take place at the tissue-implant interface.”\textsuperscript{182} In the case of surgical tools, the previous sentence can be applied by substituting “device” for “implant”. One might argue a surgical tool is merely a very short-term implant that must succeed in its intended purpose in its intended tissue environment. Subsequently, designing a surgical tool relies heavily on knowing the environment in which it will be used and the associated material properties.

The design process of a medical device relies heavily on testing, both computer and experimental, using materials of known properties. When using FEA as a design tool, an accurate material model of the animal tissue needs to be used so the animal studies can be correlated, either positively or negatively, to the theoretical results. For early bench-tests, a simple setup will be used as a rough simulation of the surgical environment. Once the device is of sufficient maturity, tissue testing using animal models will ensue. However, both the bench-top setup and animal tissue testing must be of adequate approximation to the eventual human surgical location. Furthermore, not only the model but its limitations must also be known.

For example, pigs have traditionally been used extensively as a model for cardiac experimentation.\textsuperscript{183} Cardiac anatomy and physiology closely resemble humans, as does the relative lack of exercise in an omnivorous species.\textsuperscript{184} So if a device were to be used in the cardiac system, studies using swine vasculature may be an appropriate approximation after human material properties have been established. Even still, care must be used when evaluating some devices. In one study of mitral valve replacement, pigs were used as the animal model.\textsuperscript{185} 30 days post-operation found extensive fibrous tissue response and subsequent valve malfunction happened earlier than other species. The authors therefore found this model to not be useful in predicting device-related thrombogenicity.

In order to know which bench-top approximation or animal model should be used, the human tissue properties must first be known. The balloon-assisted endoscope overtube is
designed to be used to cross three organs: stomach, colon, and vagina. For the purpose of this paper, the gastric access route will be the main focus. In the literature, there lies a very large gap in information regarding the mechanical properties of human gastric tissue. Many researchers are interested in the dynamic response of antral motor function and gastric emptying through the use of endoscopy, manometry, and radiography. Additionally, researchers have analyzed the gastric tone using a barostat, but they assumed the fundus is sphere of homogoneous tissue in location and fiber orientation. Clearly more work is needed on organ tissue homogeneity, fiber orientation and the mechanical properties of the tissue itself.

In a study conducted by Gregersen et al. the mechanical properties of human gastric tissue was looked at, though in living test subjects. Using balloons inserted into patient’s stomachs, the stretch ratio and Cauchy stress and strain were calculated from taking measurements of pressure, diameter, and wall thickness using B-mode ultrasound in the circumferential, radial, and longitudinal directions. The balloons were filled in a stepwise function with saline in volumes up to 60ml. See Figure 2-1 for a graph of the stretch ratio compared to the balloon fill volume in the three directions.

![Figure 2-1: Stretch ratio versus volume in circumferential, longitudinal, and radial directions](image)

It is seems from Figure 2-1 that the mechanical properties of the stomach are direction dependant. This is likely because the stomach can be thought of as a composite laminate made up of multiple layers of directional fiber orientations. If one assumes muscles to be a composite material, the strength must be higher parallel to the fibers than in the perpendicular direction. In a perpendicular tensile strain, the connective tissue (similar to
epoxy in a carbon fiber laminate) must support the bulk of the force. This connective tissue is rather weak in comparison to the muscle fibers, and therefore we have a lower stress value. Full differentiation of the layers is shown in Figure 2-2 and the fiber orientation in Figure 2-3.

![Figure 2-2: Full differentiation of the muscle layers](image)

![Figure 2-3: Fiber orientation, A) longitudinal layer (fibers split at black circle), B) circular layer, and C) the oblique layer](image)

Of additional importance to the work for this thesis is the stress-strain graph or, as Gergersen et al. have reported, the stress-stretch ratio in Figure 2-4. This information can be input into the FEA program as the material model. In the experiment that is reported in this graph, the authors attempted to quantify the effect of the stress-strain relationship with and without the administration of butylscopolamine – a drug used for relaxing the smooth muscle cells of the stomach wall. This would theoretically give a more true
representation of the tissue properties by inhibiting the contraction of the muscle fibers thereby skewing the results of the experiment.

Figure 2-4: Stress vs. stretch ratio in the circumferential direction

The X-axis of this graph are unconventional because the unit of strain is more commonly seen, not stretch ratio. The two are essentially the same since stretch ratio (also referred to as the extension ratio) can be expressed as shown in Equation 2-1 where $\lambda$ is the stretch ratio and $\varepsilon$ is the engineering strain:

\[ \lambda = \frac{l}{l_0} = 1 + \varepsilon \]  

Equation 2-1

Rearranging this equation for strain, the following equation can be used to transpose this information into a more standard stress-strain relationship using Equation 2-2. The data points were extrapolated from the graph using this equation and the results are reported in Figure 2-5.
\varepsilon = \frac{\Delta l}{l} = \frac{l_{\text{final}} - l}{l} = \lambda - 1 \quad \text{Equation 2-2}

Stress-Strain plot for circumferential direction during \textit{in vivo} saline-filled balloon expanded stomach experimentation

![Stress-Strain Plot](image)

**Figure 2-5: Stress-strain plot for in vivo stomach experimentation**

These experiments directly above were carried out experiments \textit{in vivo} on live patients. Because of this, it is fairly safe to assume the stomach tissue was not tested to anywhere near complete failure. Therefore, though the data in Figure 2-5 appears to be of good quality, it is not useful for FEA studies because there is an incomplete data set for the material model.

In addition to the direction of the muscle fiber affecting the uniaxial test data as shown by Gregersen et al., but the location is also quite important. In previous works, an assumption was made that the tissue properties of the stomach were homogeneous, however Lio et al. and Zhao et al. showed through experimentation in the rat and rabbit stomachs that there exists a difference in tissue properties in different anatomical regions.\textsuperscript{197,198,199} During experimentation in the rat and rabbit stomach, Zhao et al. were able to confirm different mechanical properties in 90 degree orthogonal strips of tissue in the forestomach and glandular portion of the stomach. Figure 2-6 shows the location and orientation of samples taken for uniaxial pull-testing of tissue and the results from this experiment are shown in Figure 2-7.
Zhao et al. continued their work from rats and rabbits and in 2008 published a paper using an animal model much closer to humans: pigs. Structurally, the pig stomach is more similar to the human stomach as it is divided into three main portions: fundus, corpus, and antrum. Figure 2-8 shows the general anatomy of the human stomach to be compared to Figure 2-9 which shows the porcine stomach tissue.
Results from the uniaxial pull testing seen in Figure 2-10 show in the porcine animal model a statistical differences of material models with p<0.001 between the anatomically different areas and muscle orientations. Zhao et al. have shown a trend starting with rats, then rabbits, and finally with porcine animal models the behavior of the gastric tissue. It only seems logical that similar trends can be found in human gastric tissue.
A more complete model of the human gastric tissue was developed in 2002 by the Russian researchers Egorov et al. They worked to compare both fresh resected and cadaveric tissues in the transverse and axial direction of the gastrointestinal tract: esophagus, stomach, large and small bowel. From their work, they discovered that the mechanical properties of these organs vary little between fresh resected and cadaveric tissue samples. Their results were also expressed in stress-stretch ratio graphs, so data points were extrapolated from the chart and replotted as a stress-strain graph, Figure 2-11.
Figure 2-11: Stress-strain plot from data from Egorov et al. for transverse gastric cadaveric tissue

Comparing the previous works graphically in one plot gives a clearer summary of the work completed thus far on quantifying the material properties of the gastric tissue – both porcine and human. First, the work by Gregersen et al. balloon expanding the human stomach was compared to that of Zhat et al. who uniaxial pull-tested porcine gastric tissue. Figure 2-12 shows the results are seemingly very similar. However, it needs to be remembered Gregersen et al. experimented on humans while Zhao experimented on pigs. Additionally, during experimentation, Gregersen et al. placed the ultrasound transducer in the epigastrium, which would equate to the fundus or possibly the corpus, yet the data more closely represents Zhao et al. data from the antrum.
Because of this discrepancy, both data sets are then compared to the data reported by Egorov et al., Figure 2-13. Despite the difficulty in determining the exact plots of the Gregersen and Zhao data, it shows clearly the small difference between the previous two experiments appears quite minor when compared to the Egorov material data. Both Zhao et al and Egorov tested human gastric tissue, so despite the later values extending much higher due to a more complete graph, the initial elastic portion of the stress-strain graph would be expected to be similar. Not only are the data unquestionably in disagreement, the data from Egorov et al. appears oddly linear whereas the other stress-strain plots are not. The lack of agreeable data on the material properties of gastric tissue – human or porcine – make any FEA simulation using said data to also be questionable. Therefore, obtaining first-hand data on the human gastric material properties of the corpus is necessary.
2.2 Human Gastric Tissue Uniaxial Pull-Testing

There appears to be some discrepancies between the data presented in the literature, and first-hand pull-test data is the only way to know with certainty the quality of the information. Human gastric tissue pull-testing began as an attempt to either validate or contraindicate any of the gastric material properties previously discussed. The testing was performed in accordance to a protocol most recently developed by Dr. Yingchun Zhang at the University of Minnesota in conjunction with Dr. Simha, referencing Fung et al., and based on previous work from Drs. Timm and Sweet.

2.2.1 Initial Tensile-Testing Experiments

In order to get a rough picture of the properties, a single set of uniaxial pull-tests were performed. A stomach was obtained from a freshly deceased donor cadaver from the Fairview Hospital, University of Minnesota and stored at 4 degree Celsius, in a solution of 9 parts Phosphate Buffered Solution (PBS) and 1 part Diluted Protease Inhibitor (DPI). The donor was a 59 year-old female, height was 165 cm, and weight was 73 kg. She passed away of unknown causes on 1-25-09 at 8:35 PM and the tissue was extracted on
1-27-09 at 2:00 PM. The tissue testing was performed on 2-4-09. At the time of testing, the tissue was removed from the refrigerator and warmed to 37 C passively by a Gaymar T pump for 15-20 minutes before testing, Figure 2-14. Water is circulated through the pump and into the aluminum coils in the acrylic tank. The container of tissue and preservation fluid is placed in water in the acrylic tank. Warming the tissue slowly and by indirect heat helps reduce the risk of tissue damage during the heating process.

Figure 2-14: Warming pump and acrylic tank to warm refrigerated tissue up to 37 C

Once warmed, a small piece of tissue was removed and the rest placed back into the warming bath. The sample was gently washed with saline and a rectangular section cut in an unknown orientation to the muscle fibers. It was then transferred to the MTS Intron uniaxial testing machine with a 50N load cell. The fixturing jaws on the MTS uniaxial testing machine were designed by Daniel Burke from the University of Minnesota. The tissue was clamped firmly between two pieces of aluminum which are positioned so the tissue remains moist in distilled water during testing, Figure 2-15.
It was initially difficult to fixture the tissue in this setup because the inner and outer gastric layers move relatively freely in relation to each other because of the loose nature of the connective tissue between the layers. This led one layer to slip to the side of the other, instead of staying layered vertically like a sandwich. The resulting tissue was difficult to maintain uniformity and keep from twisting, and because the effect of holding the tissue in this fashion was unknown, the inner and outer layers of the stomach were tested independently. Once tissue was clamped in the testing apparatus, any excess that extended beyond the width of the jaws was cut off as to not inadvertently add error into the testing. The width of the tissue sample was taken in three locations with a dial caliper to be input into the Microsoft Excel macro after testing was complete. It is much harder to use standard measuring tools to obtain accurate thickness readings, and therefore an optical measuring device was used to take multiple figures for the Excel macro.
Part of Dr. Zhang’s tensile testing protocol called for preconditioning of the tissue, prior to the full test-to-failure. Preconditioning is a process by which the tissue is stretched slightly and relaxed several times in order to reduce the hysteresis loop during relaxation. The tissue is thought to respond to the preconditioning due to strain softening in reaction to the loading. Figure 2.17 shows the nine preconditioning cycles used during Test 5 – outside layers of the stomach tissue. Note the decreasing distance between tests until a high degree of repeatability is achieved.

A series of three tests were performed on both the inner and outer layers of the gastric tissue; named “Old Test #” denoting the relative age of the test for this research. Tissue
was pulled at a strain rate of 0.1mm per second. The raw data is processed using a custom analysis program in Microsoft Excel. One of the tests for each of the layers failed, so only two data sets were adequate to post process. The results and averaging of the inner layers can be seen in Figure 2-18, while those of the outer layers can be seen in Figure 2-19. Averaging of the curves was performed using OriginPro 8.1 (OriginLab, Northampton, MA) which uses a complex interpolation process to first interpolate the graphs to find common x-values, averages the y-values, then interpolates again to reduce the data set to 1000 points. Units for the stress are noted in the graphs.

![Figure 2-18](image1.png)

Figure 2-18: Results and average of initial testing of inner layers of cadaveric human gastric tissue

![Figure 2-19](image2.png)

Figure 2-19: Results and average of initial testing of outer layers of cadaveric human gastric tissue
Analyzing the differences between the two averaged curves leads to some interesting theories. Despite the fact that the inner layers have a higher peak stress than the outer layers, after the yield strength of the material has been reached, the residual strength of the material greatly diminishes for increasing strain values. Conversely, the outer layers plot shows a behavior more typical of a polymer because after the initial yield and fall of strength, a secondary peak is seen. With polymers, this is due to fiber reorientation into the direction of the uniaxial pull and subsequent yield of these fibers. This would make sense for the outer, more muscular layer. The muscle fibers may behave similar to polymer fibers, rearranging during the pull-test giving the graph the characteristics and the material the residual strength after initial yield that is seen in Figure 2-19.

One more interesting point to note is the ability for the tissue to continuing to take additional strain well beyond the initial decrease in strength. This ability is due to the tissue’s similarity to fiber-composite materials. Instead of a fracture pattern similar to metals where an initial fracture propagates across the width of the material, observations during testing revealed fibers of the tissue breaking individually. This would be consistent with the graph; the strain continues to grow and more fibers break leading to decreased strength and therefore decreased stress levels. This cyclical pattern continued until the last fiber of tissue was broken.

Figure 2-20: Pictorial process showing progression of tissue fracture during tensile testing
Though the results were interesting, the initial round of uniaxial pull-testing did little to solidify the actual material properties of the gastric tissue. It is unknown how the two layers of tissue interact to makeup the full strength of the material. Another round of testing was performed, this time taking extra care to orient the tissue correctly on the jaws and keep the layers properly aligned.

The second donor was a 62 year-old female, height was 157.5 cm, and weight was 117.9 kg. She passed away from liver disease due to alcohol on 11-12-09 at 11:15 PM and the tissue was extracted on 11-13-09 at 1:15 AM. Tissue testing was completed on 11-18-09. Seven tests were performed on this tissue, six in parallel to the orientation of the muscle fibers in the fundus and one orthogonal. The same testing protocol was used as with the previous tissue testing, and the data were post-processed using the same techniques. Unfortunately, three were determined to have failed due to tissue slippage and incomplete breakage and were subsequently removed from the data set. The results and the average of all three graphs using OriginPro 8.1 can be seen in Figure 2-21.

![Comparison and Average of Pull-Test data from Test 2, Test 5, and Test 6 - Bulk Thickness](image.jpg)

**Figure 2-21:** Results and average of testing bulk thickness cadaveric human gastric tissue
From this plot it is obvious to see that Test 2 appears to be an outlier in this data set. As stated earlier, three of the other tests had been discarded due to failure to complete the testing protocol, but since this test did complete the protocol adequately, the results were included. It was startling, however, that the maximal stress found in Test 2 was over 50% larger than the maximal stress in either Test 5, or Test 6 – despite the samples all being taken from the same portion of the donor stomach. This shows two very important features about pull-testing biological tissues: 1) there is a large variability within tissue – it is not homogenous, and 2) obtaining repeatable results from testing tissues is difficult. Either one, or both, of these scenarios could have lead to the differences. Perhaps there was a blood vessel, or other anomaly in the tissue in Test 2. Or, Test 2 may be the actual material properties, and both Test 5 and Test 6 were inadequate samples. In either case, the average from all three tests was calculated. In addition, the average of the two most closely related graphs – Test 5 and Test 6 – were taken. More tests are needed to determine if, in fact, Test 2 is an actual outlier or merely on the upper end of acceptable material properties.

It is interesting to note, however, that the tissue did not have material properties that hugely differed from the prior study of the separated layers. A plot of the averages from all the different sets of data was assembled for comparison and can be seen in Figure 2-22.
Figure 2-22: Comparison between uniaxial pull-testing of human gastric tissue

Though the samples sizes are too small for statistical analysis, some comparisons can still be drawn. First – not surprisingly – the bulk tissue has a higher peak stress than the separated layers. Even when the outlier Test 2 is removed from the bulk tissue averaging, the peak stress still rises above that of either the inside layers or outside layers when tested separately. Additionally, it appears as though the plot of the bulk tissue is a composite of both the inner and outer layers. The inner layers had a higher peak stress than the outer layers, but the outer layers had more residual strength from the muscle fibers than the inside layer. Both traits can be seen on the bulk tissue plots. The peak stress rises quickly, but the tissue also appears to have a bit of residual strength more characteristic of the outer layers – though not entirely characteristic as the bulk tissue does not have a secondary local maximum.

When the bulk tissue was tested orthogonal to the muscle fiber direction, the plot is nearly identical to the inner layers, but with a much higher peak stress. Remembering that this is merely a single test, the high peak stress could be attributed to both layers of tissue combined instead of merely the inner or outer layer alone. The reason for a quickly diminished residual strength would be attributed to the lack of the muscle fibers to maintain strength in being pulled this direction. Muscle tissue is strongest in the direction of the fibers.\textsuperscript{202} In a perpendicular direction, muscle is mostly held together with
connective tissue, and thus the strength of the muscle fibers becomes minor to the bulk properties as the fibers can not add strength in a direction they are not aligned.

The final comparison to be made is how each of these plots discussed thus far correlates to the data from Egorov et al. Though the accuracy of the data has been questioned due to the lack of any other paper or data set to even remotely recreate their data, it has been a useful tool in setting a standard to compare every other graph to. Figure 2-23 shows the vast difference between the data generated for this dissertation and that pulled from the Egorov paper.

![Stress-strain plots comparing curves for multiple experiments](image)

**Figure 2-23: Comparison of uniaxial pull-test data of the human cadaveric gastric tissue to the data extracted from Egorov et al.**

When referring back to Figure 2-13 – in which the data also disagrees with Egorov – the data sets are all very different from each other. Figure 2-10 and Figure 2-23 were merged to form Figure 2-24 to show more clearly these variations; some graphs were removed from each figure to more clearly show generalizations in the reported data. Clearly, despite testing the same material, significant differences between data occurred. The testing methods were similar, but slight variations in tissue handling, fixturing methods, and pull rates were analyzed for the source of this discrepancy.
Figure 2-24: Comparison between test data and data from the literature by Egorov, Zhao, and Gregersen

The first source of discrepancy was in the method of tissue handling each group used prior to the uniaxial pull-testing. While Egorov et al. and the author stored the tissue in a refrigerator at 4 degrees Celsius between the tissue was used for testing, Zhao used freshly excised porcine tissue testing within one hour after removal. This tissue was stored in a cold Krebs solution (6.89 NaCl, 0.35 KCl, 2.1 NaHCO₃, 0.16 NaH₂PO₄, 0.24 MgCl, and 2.1 glucose) with 3.0mM EGTA aerated with a gas mixture of 95% O₂, and 5% CO₂ and a pH of 7.4 during the transfer period. The sample was not warmed to physiological temperature and was bathed in the same fluid during testing. During the time that Egorov stored the tissue, it was immersed in physiological saline, and was not immersed in any fluid during the testing – which could skew the data if the tissue dried out during testing. Finally, the author used a solution of 9 parts PBS and 1 part DPI, and used distilled water to bath the tissue during testing.

Second, Each of the sets of pull-test data used unique methods of holding the tissue. Egorov used a pneumatic clamp preset to an initial length of 25mm. Zhao tied silk threads onto the tissue which were attach to a cannula fixtured to the testing machine and then measured the initial length. Finally, the author used a mechanical clamping force from set screws in an aluminum bracket and measured initial distance from that. It is
possible that when Zhao et al. tied the silk thread to the tissue, some slippage occurred. In this case, the data would show an unusually high strain for the stress levels seen because the tissue would be artificially lengthening due to extra distance between fixation points. Even still, this doesn’t explain the correlation of the data between Zhao et al. and Gregersen et al. who reported relatively similar gastric tissue mechanical properties, despite the extreme difference in arriving at their results. Zhao et al. performed pull-testing, while Gregersen et al. used ultrasound to determine the properties of the gastric tissue.

The final difference between the three uniaxial testing procedures – and perhaps the most important – lies in the strain rate of the testing. The author used a strain rate of 0.1mm/s, equivalent to 6 mm/min. Egorov and Zhao both used strain rates of an order of magnitude higher, 60 mm/min and 30 mm/min respectively. It is possible to see different results based on a higher strain rate during the pull-testing. In order to validate this theory, it would be necessary to test the tissue at varying strain rates to see the effects this change has in the recorded material properties.

Due to the extreme difference in testing procedures Gregersen et al. used to determining the material properties of the human gastric tissue, it is difficult to determine the validity of their results in comparison to the pull-testing results from above. Gregersen et al. used an ultrasound probe to record changes in stomach tissue thickness during a balloon-distension procedure. However, the alterations in the tissue thickness are not necessarily all dependant on the pressure exerted by the balloon. When the balloon is inflated, it could put unequal pressure on various parts of the stomach when it expands. Furthermore, when the organ expands and presses against other internal organs and anatomy, the thickness of the stomach tissue can be affected unequally.

Despite all the variations and discrepancies in the data between research groups, data produced by the author are believed to be valid for the purposes of this dissertation. Results have been shown to be repeatable over several months with different donor organs. Additionally, the procedures used to test the gastric tissue has been used by another research group at the University of Minnesota for various other soft tissue hollow
organs with great success for other research projects. In an attempt to assume a more statistically accurate set of material properties of the human gastric stomach, additional tests using the same testing protocol described above were performed.

### 2.2.2 Bulk Tissue Material Properties

Perhaps the most important material property – for the purposes of the eventual FEA studies – is that of the bulk tissue. Knowing the layered material properties becomes of interest after the bulk tissue is fully characterized. Increasing the number of tensile tests performed using the same protocol and techniques described above will increase the degree of certainty of the bulk data. Several more series of ten tensile tests were performed on the human gastric tissue taken from the fundus. The samples were cut from the same portion of the stomach to achieve a more accurate average of the given tissue, Figure 2-25.

![Figure 2-25: Location and numbering of gastric tissue tensile testing for bulk thickness parallel to muscle fiber location](image)

Each strip of tissue was cut from the tissue and identically prepared as follows: Once the rectangular specimen was removed, a tool was used to create a 4 French (1.333 mm) semi-circular notch on either side in the middle to create a dog-bone shape. This was because otherwise the load and displacement needed to test to failure was outside the range of the testing apparatus.
Throughout the course of this research, gastric tissue from several donors was tested as the material became available. This produced a large amount of surprisingly differing data sets. A sample of one day of tensile testing can be seen in Figure 2-26. While individual tests are difficult to differentiate in this figure, it is important to note the large variability possible when testing biological tissues. Even still, trends such as the strain at maximum stress, and the relative shape of the stress/strain plot are established.

![Material Properties of Human Gastric Tissue](image)

*Figure 2-26: Bulk thickness tensile testing in direction of muscle fiber direction, performed 01-19-2010*

To completely understand the variation material properties of the tissue in parallel to muscle fibers, all data from the tensile tests was compiled into a single plot, Figure 2-27. This plot differs greatly from Figure 2-26 as it can be seen there is much less uniformity in the individual tests – both between testing days and within each donor sample. Figure 2-27 is meant to show the solution space from tensile testing human gastric tissue. The only individual tests that are of importance are the two clear outliers. Figure 2-28 goes one step further and shows the average curves of all data with and without these outliers.
Figure 2-27: All data from tensile testing gastric tissue in parallel with muscle fiber direction

Figure 2-28: All tensile test data including the average of gastric tissue parallel to fiber direction
From Figure 2-27 it can be seen now that the previous assumption of T2 091118 being an outlier due to a high maximum stress was incorrect. It was merely at the top-end of a range of values that had previously not been fully realized. Instead, it appears as though T2 091118 may be an outlier because it has stress values of between 2 – 7 times higher over the strain values of other tests. Additionally, T1 091125 is an outlier of the data as its maximum stress value is approximately 70% higher than any other data set. An average of the data in full, and minus each of the questionable data sets was taken to observe the difference in the resulting material property curve. Though included in Figure 2-28, a more detailed plot was created and is shown in Figure 2-29.

![Comparison Between the Average of Data](image)

**Figure 2-29: Comparison between averages of tensile testing excluding various data sets**

It is seen that even when the outlier data sets are included in the overall average, the resulting plot does not have a great deal of variation. Though the values from the extraneous data sets differ greatly, the average is not affected much because of the larger number of tensile tests. Notice when T1 091125 is removed (very large peak stress), the
peak stress of the average also moves down slightly. This difference appears small, but the peak average is 11.9% higher than when T1 091125 is removed.

While removing T1 091125 altered the peak stress, removing T2 091118 has a profound impact on the decaying portion of the graph. The shape of T2 091118 was previously thought to be an effect of muscle fibers being able to retain residual strength after initial yield. This was an incorrect assumption, and the shape is rather a display of an inaccurate test. Even though the effect T2 091118 has on the average is well into the damage portion of the tensile test, it nevertheless was considered an outlier and was removed. It seemed sensible, in the name of conservatism, to exclude both T2 091118 and T6 091118. This resulted in a material model with lower peak stress and steeper damage decay, but which will lead to a higher margin of safety for an average tissue sample enduring strain due to balloon expansion from the designed device. The peak stress from this plot is found to be 169,660Pa at a strain value of 0.304.

An initial conclusion made from the first round of tensile testing still holds true after more data was added – the material properties of the human gastric tissue differ greatly from any gastric tissue reported in the literature. The trends in material properties found in initial tensile tests at the University of Minnesota – seen in Figure 2-24 – disagreed with plots reported by Gregersen, Zhao, or Egorov. After further testing of different donor tissues, the data produced for this research was found to be repeatable, and therefore the data produced through this tensile testing is thought to be the most accurate data to date.

2.2.3 Anisotropy of Human Gastric Tissue

It had been shown in Figure 2-1, Figure 2-7, and Figure 2-10, by Gregersen et al. and Zhao et al. that there are material properties for gastric tissue depending on the direction – zero vs. ninety degree orientations. This anisotropy has been explained by the multiple multi-directional layers of musculature. Each layer has different properties than the next so the resulting composite material has different uniaxial properties depending on the direction of the pull. While Gregersen et al. tested anisotropy of gastric tissues in the
human model, it was not a complete test of the full material properties. Furthermore, Egorov et al. performed uniaxial tissue-testing in the transverse and axial directions of the human stomach, seen in Figure 2-30. However, as previously discussed the validity of the data produced by Egorov et al. is questionable because no other reported data set has been able to approach the same maximum stress. Therefore, an investigation into the anisotropy of human gastric tissue was initiated.

![Comparison of Egorov Orthogonal Uniaxial Pull-Test](image)

**Figure 2-30: Comparison of orthogonal directions of human gastric tissue by Egorov et al.**

The data presented in the previous section completes the portion of the anisotropy study in the direction of the muscle fibers. Next, a similar study was conducted with the samples cut perpendicular to the muscle fibers. Again, the anterior fundus portion of stomach was used to most accurately average and compare the material properties to the previous work. Samples perpendicular to the muscle fibers were taken as shown in Figure 2-31.
Each strip of tissue was cut and prepared in the same fashion as those used for the parallel tensile testing. A 4 French (1.333mm) semi-circular notch was created in each sample to decrease the width of the strip so the force and displacement of the testing machine would accommodate the material. One set of testing was performed on 1-19-2010, and the results can be seen in Figure 2-32.
In order to fully realize the material properties of gastric tissue perpendicular to the muscle fiber orientation, several more tests of different stomachs were performed. All tests and the average are combined into a composite graph seen in Figure 2-33.

![Material Properties of Human Gastric at 90 Degree Orientation](image)

**Figure 2-33: All data from tensile testing gastric tissue in perpendicular with muscle fiber direction**

The data from tensile testing human gastric tissue perpendicular to the muscle fiber orientation shows a less organized series of graphs than those in parallel to fiber orientation. The reason for this is still a bit unclear, however, it is encouraging to see a few slight trends in the data. The tensile tests show an average peak stress at a strain value of 0.316. This is important for two reasons. First, the newly obtained data again starkly contradicts previously published data by Egoroc, Zhao, and Gregersen. Secondly, the peak stress corresponds closely with the data obtained in tensile testing parallel to muscle fibers.

Egorov et al. achieved a maximum perpendicular stress at a strain of 1.29 – over 400% larger than has been shown here. By the time a strain value of 1.29 is found in Figure 2-33, the tissue has essentially completely broken as the stress value has been reduced to
nearly zero. Unfortunately, both Zhao and Gregersen reported data that does not appear to have been tested-to-failure so there can not be comparisons drawn based on max stress. However, the perpendicular data seems to follow similar trends as the parallel data of the material properties over multiple tests, tissue samples, and testing dates seems to be repeatable. This repeatability gives confidence in the accuracy of the newly found data.

The data published by Gregersen, Zhao, and Egorov all found slight differences between the material properties in parallel and perpendicular to muscle fiber orientation. Despite these differences, the perpendicular plots were relatively close to their orthogonal counterparts. It can be seen that similar to the other researchers, the data for both directions are fairly uniform. Other than the difference in the maximum stress – parallel being only 6.5% larger than perpendicular – the two plots are nearly identical in all other aspects. Figure 2-34 shows the averaged curves for the two testing methods plotted on the same graph.

![Comparison Between Parallel and Perpendicular Tissue Properties](image)

**Figure 2-34:** Average curves of bulk tissue tensile testing in parallel and perpendicular to muscle fiber orientation
Similar to Zhao et al, the tissue parallel has a slightly sharper rise in stress for similar strain values over the perpendicular. This same trend was seen in Figure 2-30 by Egorov (transverse refers to perpendicular, and axial refers to parallel directions). Even still, due to the large variability of data measured in the present experiments, the statistical significance of these differences is questionable. The plots are nearly identical, and each has a very large standard deviation, see Figure 2-35 (A) and (B) for plots showing the error bars (seen as a cloud around the line). The data overlap demonstrates that a statistical analysis is not needed to determine there is no statistical significance. Thus, for the following work there is no data that clearly shows the difference between the material properties of human gastric tissue in parallel and perpendicular to muscle fiber orientation.

![Figure 2N35: Averages of data in parallel and perpendicular direction showing error bars](image)

#### 2.2.4 Gastric Tissue Layers Material Properties

Indeed, significant testing could be completed by isolating layered material properties and describing how each layer interacts to produce the full thickness properties. However, a simple study was conducted here to attempt to begin to grasp how the inner and outer layers contribute to the bulk thickness strength. If one layer has considerably different properties than the other, the strategy for safely penetrating through the gastric tissue may need to be altered. A test was created to determine if the outer layer considerably stronger or weaker than the inner layer of the gastric tissue?
Two tissue samples were taken and dissected to isolate the inner layers from the outer layers of the gastric tissue. The layers were dissected through the submucosal plexus of Meissner, Figure 2-2. This thin layer forms a natural break between the mucosal stomach lining, and the muscular outer layers. Once separated, the tissue was cut into specimens sized for the MTS tensile testing machine in the same fashion as bulk tissue testing. Inner and outer layers were tested and averaged separately,

![Material Properties of Human Gastric Tissue - Inside Layers](image)

**Figure 2-36: Composite and average of all tensile testing of inside layers**

![Material Properties of Human Gastric Tissue - Outside Layers](image)

**Figure 2-37: Composite and average of all tensile testing of outside layers**
Looking at the above figures, it can be seen that both inside and outside layers portray a surprising similarity. Both have peak stresses at nearly the same strain level, about 0.35. Each also has a disturbing amount of randomness. The largest peak stress was over 2.5 times larger than the smallest peak stress for the inside layers, and over 4.8 times for the outer layers. The discrepancy in the outer layers quite obviously comes from an apparent outlier in T35 100119-O. Upon analyzing further, the peak stress seen in this plot is 160% larger than the next highest peak. Additionally, though not quite as obvious, the max stress seen in T25 100119-O is less than half the value of the next largest tensile test. Each of these is well outside the standard deviation of the data set. However, due to the limited number of data for this test, both of these data sets will be included for the average calculation.

One fairly unexpected result of this experimentation, however, was a higher average maximum stress levels from the inner layers than from the outer layers was found. Figure 2-38 shows the relative differences. The peak stress seen in the inner layers is 42% larger than the peak stress seen in the outer layers. This discrepancy requires a bit more statistical analysis than what was needed for the parallel and perpendicular layers.

![Comparison Between Inside and Outside Layer Tissue Properties](image)

*Figure 2-38: Differences between inside and outside gastric tissue layers*
The first step to the statistical analysis was to add error bars onto the averaged data, see Figure 2-39. From this figure, the data between a strain of 0.27 to 0.72 is especially of concern because this is the area that the inside layers is outside the standard deviation of the outside layers, even though the reverse is not true. In order to determine statistical significance, the data must be analyzed for normality. Despite the appearance of a solid line, each of the curves is actually a composite of discrete points; each of which is an average of all experiments at a particular strain value with its own mean and standard deviation. Therefore, there may be areas of the curve that are normally distributed and others that are not. A data set (or a point in this case) is said to be normally distributed by finding the skew number,\(^{203}\) and comparing it to twice the standard error of skewness (SES).\(^{204}\) If the skew number the lesser of the two numbers, the data is normal. This was done for each data point for both data sets and plotted together to see the areas of normality and skewness. Figure 2-40 shows the resulting areas of normality and skew. The bulk of both curves are considered normal. The skew number for each curve shows that while there are areas that are not normal because the skew number is larger than the calculated 2XSES, the assumption for normality can still be used; however, any statistical significance found in these regions is suspect to a greater degree of scrutiny.\(^{205}\) Both the normal and non-normal areas of the plot were subjected to an analysis to determine if they could be determined statistically different.
It is important to remember for the following statistical analysis that whole curves are not being compared, but rather data points paired at the same strain value from the inside and outside material property plots. For normal data points, a two-sample t-statistic of unequal variances is calculated for two different null hypothesis to determine statistical significance; \( H_0: \) inside layers > outside layers, and \( H_0: \) the means are equal. The paired data points for each curve have the same strain values, but differing stress values. Simply looking at the plot of Figure 2-40, due to the large vertical difference it appears as though a region of statistically differing data seems possible from a strain of approximately 0.3 through 0.8. This makes the analysis much simpler because the graph can be thought of in three regions: non-significant for low strain, significant in the middle, and non-significant near the end. This simplifies the analysis because statistical significance will not need to be tested at every point; only the critical point at each transition needs to be found.

The raw data for the tensile tests for the inside and outside tissue layers were input to a worksheet in OriginPro 8.1. Using a statistics function inherent in the program, a null
hypothesis of, $H_0$: inside layers > outside layers was selected. Strain values were chosen, corresponding stress values were selected and analyzed for statistical significance, and the process iterated until the critical strain value was found where the p-value < 0.05. The process was repeated again for, $H_0$: the means are equal. For both statistical tests, the formula used for finding the t-statistic is found in Equation 2-3\textsuperscript{206}, and the resulting p-value is interpolated from a table with significance level in columns, and the degrees-of-freedom (DOF) listed in the rows. Figure 2-41 shows the critical strain values for a p-value < 0.05 for both null hypotheses where the circle points refer to, $H_0$: inside layers > outside layers, and the diamond points refer to, $H_0$: the means are equal. Random points were selected and analyzed to ensure that all points in between are statistically significant at a level of 0.05.

$$T - \text{statistic} = \frac{\bar{X}_1 - \bar{X}_2}{\sqrt{\frac{s_1^2}{n_1} + \frac{s_2^2}{n_2}}}; \bar{X} = \text{mean}, s = \text{stddev}, n = \text{sample size}$$ \hspace{1cm} \text{Equation 2-3}

Figure 2-41: Regions of statistical significance overlaid on plot of areas of normality for inside and outside human gastric tissue
The main difference in finding the p-value between the two different null hypotheses is in the DOF. For, $H_0$: inside layers>outside layers, the DOF is calculated by Equation 2-4, whereas for, $H_0$: the means are equal, the DOF is taken to be the smallest of $n-1$, where $n$ is the number of samples for each averaged data point. For example, at a strain value of 0.5, the DOF of, $H_0$: inside layers>outside layers is 8.99203, and the DOF of, $H_0$: the means are equal is 6. It can be seen from Figure 2-41 the region between the diamonds is smaller than between the circles. The null hypothesis of, $H_0$: inside layers>outside layers uses a one-sided t-test to determine statistical significance while, $H_0$: the means are equal uses a two-sided test. This, along with the difference in DOF, means even though the same t-value is used, statistical significance is more easily achieved for, $H_0$: inside layers>outside layers. Statistically, it is easier to determine one mean is larger than to determine if the means are statistically different. The strain values for which the mean of the inside layers are statistically different from the outside layers is only from 0.304 – 0.454, while inside layers are statistically larger than the outside layers from a strain of 0.282 – 0.674.

$$DOF = \frac{s^2 \left( \frac{s_1^2}{n_1} + \frac{s_2^2}{n_2} \right)^2}{s_1^4 \frac{1}{n_1^2} + s_2^4 \frac{1}{n_2^2}}$$

$s = \text{stddev, } n = \text{sample - size}$  

Equation 2-4

Considering Figure 2-41 with an end-result of inputting data into a FEA program for use by medical device engineers, several interesting conclusions can be drawn. First, despite the worry of normal and skewed data, the regions of statistical difference lie completely within the area of normal data distribution; with the exception of 10 data points on the outside data curve which are just barely outside the skew statistic range for $H_0$: inside layers>outside. This means that the calculation of the t-statistic to find the p-value is an accurate statistical method to determine significance. Furthermore, it is also interesting to note that though the peak stress for the inside layers is found to be both statistically larger and different than the peak stress for the outside layers, but the reverse is not true. However, even though a non-negligable portion the tissue plots are statistically different
(strain value of 0.304 – 0.454), and the inside layer is statistically larger (strain value of 0.282 – 0.674), the bulk of these regions lie in the break-down portion after peak stress of the material properties. This area is not as important to devices such as the one proposed by this research because the aim is tissue preservation, not with tissue degradation.

For the purposes of designing medical devices, it would therefore seem prudent to regard the inside and outside layers of human gastric tissue to be roughly equivalent to each other. They can both be approximated to be equal; meaning tools that will interact with these tissues can be expected to behave the same with both tissues. When using numeric models for the stress-strain data in a FEA simulation, however, it would be more accurate to differentiate the models if the model is sufficiently detailed enough to warrant such an action. Extreme caution must be used in such simulations, though, because the interaction between the two tissues from the thin connective tissue to obtain full-thickness gastric tissue models has not been explored. Until this interaction has been fully captured, a full-thickness model is still the most useful. Even still, this research shows a slight variation between the inside and outside layers of the human gastric tissue. Together with the knowledge of the ability of the layers to be manipulated to some degree with respect to the other may be of increasing importance as more NOTES research groups consider the gastric organ as a method of access for peritoneal cavity interventions.

### 2.3 Silicone Tissue Substitute

In order to validate the finite element model, a tissue substitute is needed which is readily accessible and easily testable. Using this material, FEA simulations are performed which should also match a physical experiment. When the computer simulations are able to match this experiment, the computer model is validated to be correct and extrapolations made to then declare the FEA using tissue also to be accurate.

A wide array of materials from textiles to polymers to fiber reinforced composites were originally evaluated for the tissue substitute. However, both textiles and fiber reinforced composites would add to the complexity of the problem due to their non-homogeneity in makeup and direction. Though the gastric tissue is actually non-homogenous in makeup
and direction, the previous section statistically showed it will be modeled as homogenous and isotropic. For this reason, the tissue substitute must also be homogenous and isotropic. A class of materials stood out amongst the rest in these characteristics and the ability to undergo high strain – polymers. More specifically, low durometer urethanes, silicones, and natural gum rubbers were investigated for their ability to undergo strains at low stresses. Of these, the low durometer silicones seemed to be a better fit to the gastric tissue than the others. Samples of several different durometers were obtained and 10A durometer silicone was selected to be the polymer tissue substitute. Unbacked silicone sheeting 0.1875 inch thick with a rated tensile strength of 200 psi (1.38 MPa) was ordered from McMaster-Carr to be tensile tested to produce full material model data points to be input into ABAQUS for FEA simulations in a similar process to the gastric tissue.

In order to ensure that the material properties are most accurate, testing standards ASTM D412 and ISO 37 were referenced. They dictate many of the variables (extension rate, temperature, humidity, geometry, preconditioning, etc.) necessary for repeatable and comparable tests to other rubbers. Even still, one statement in ASTM D412 was found to be more important than the actual described testing parameters: “Tensile properties depend both on the material and the conditions of test; therefore materials should be compared only when tested under the same conditions.” The silicone material in this instance is not being compared to other silicones, but to the gastric tissue. Therefore, in order to maintain similar variables for the most accurate experimental representation possible the silicone was tested using the same machines/setup and under the same protocols as previously used (50N load cell, 0.1mm/sec load rate, 9 preconditioning cycles).

Due to the relative uniformity of the silicone when compared to human tissue, far fewer tensile tests were needed in order to capture the material properties. A small piece was cut from the larger bulk material and reduced further in size until it was approximately 20mm x 1.41mm x 1.86mm (length x width x thickness). The sample was fixtured in the jaws of the tensile testing machine and the protocol run. Due to the large amount of
elongation the silicone was capable of, the sample did not completely break. Several more tests were performed with decreasing cross-sectional area in an attempt to fully break the material. Two unfortunate side effects occurred, however: 1) the machine continually ran out of travel before full breakage could occur, 2) as the cross-sectional area decreased (Table 2-1), the noise and scatter of the stress-strain data increased. All data from the testing was plotted to show the differences, Figure 2-42.

<table>
<thead>
<tr>
<th>Test Number</th>
<th>Width (mm)</th>
<th>Thickness (mm)</th>
<th>XC Area (mm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1</td>
<td>1.4100</td>
<td>1.8600</td>
<td>2.62260</td>
</tr>
<tr>
<td>#2</td>
<td>2.1590</td>
<td>1.1090</td>
<td>2.39433</td>
</tr>
<tr>
<td>#3</td>
<td>1.0583</td>
<td>0.6773</td>
<td>0.71679</td>
</tr>
<tr>
<td>#4</td>
<td>0.4318</td>
<td>0.4064</td>
<td>0.17548</td>
</tr>
</tbody>
</table>

Table 2-1: Silicone sample cross-sectional area

During testing, it was found that the percent elongation of the silicone was much higher than the gastric tissue. This resulted in the initial test being unable to break the material. It was then though if the cross-sectional area were reduced, then the silicone may break due to an increase in stress. However, the only effect this had was to increase the error
and variability in reported stress levels. With decreasing width and thickness, the same size absolute error in measurement would lead to a much higher percent error. Since stress is calculated from these dimensions, it is intuitive for this to lead to more variability in reported data. To determine an average silicone material property, all four tests were initially used, Figure 2-43.

![Graph showing material properties for 10A durometer silicone](image)

**Figure 2-43: Tensile test data and average of 10A durometer silicone**

Test #4 had a large amount of scatter, and it appeared to skew the results to show higher stress values than what actually may be. Test #4 was eliminated and new averages were calculated. However, after a strain of 0.932, test #3 had no more data, and the same occurred for test #2 after a strain of 1.457. The average of the data was calculated based on the number of tests in a given strain region: all three test from 0 – 0.932, and Test #1 and #2 for 0.932 – 1.457, Figure 2-44.
Figure 2-44 still does not represent a full material property plot, however. It is clear that the two averaged curves form a discontinuous line. They also do not extend fully to capture all of test 1. The final step in creating the full material model for the 10A durometer silicone was to extrapolate and offset the averages to form a continuously smooth curve. Looking at the average plots, they follow very closely the plot of Silicone 1. Also, due to averaging only from 2 tests, the second average has a Y-offset. Finally, in order to complete the material model, data was extrapolated past the average of tests 1 and 2 using data from test 1 with a Y-offset. The final plot can be seen in Figure 2-45.
It is fairly obvious to see that the trendline to be used for the material property definition is different from the tissue model in two ways. First, the silicone data begins in low strain as a decreasingly positive slope, whereas the tissue begins as an exponential climb. This slight deviation in low strains has little difference in the way ABAQUS will use the information or the ability to validate the tissue model from the polymer. The second, however, has a significantly different outcome; the silicone data never stress-softens the way the tissue did. The silicone data maintains a positive slope for the entire set of strains tested. This does not reflect complete irreversibility, though. During tensile testing, it was physically observed that when the test cycle was complete and the jaws returned to the home position, the silicone sample would be plastically deformed and appear as though necking had occurred. The stress-softening occurred in the tissue from breaking of the tissue fibers – fibers which were not present in the silicone sample. While this feature is a significant deviation from the gastric tissue model, due to the unique nature of gastric tissue, a very close match is very improbable. Even still, many FEA assumptions – such as the hyperelastic model, boundary and initial conditions, loading/displacement
techniques, contact interactions, and adaptive meshing – are still able to be tested for accuracy.

2.4 Overview

Initial experiments into the material properties of human gastric showed an interesting deviation in data when compared to the literature. Not only were peak stress values considerably different, so were the resulting shape of plots. After several discussions with lead researcher Zhao, the reason for the differences between the plots from the literature and these experiments are still unclear, though the strain rate during tensile testing is highly suspect.

A more detailed analysis showed that the previously described anisotropy of the gastric tissue in parallel and perpendicular directions in the fundus were questionable in humans. Though some individual tests showed slight differences, when averaged together the two plots are essentially indistinguishable. One possibility for this deviation from the literature could be with the sample size used in the testing. The tensile testing apparatus used for this research required a very small specimen of tissue, and the resulting material properties were more dependant on the exact area where the sample was cut from, and less an average of the whole tissue. This was attempted to be mitigated by taking multiple samples parallel to each other, thereby finding the average properties of that larger area of tissue. An interesting study would be to use a different testing machine capable of larger loads and strains allowing the test specimen to be larger and therefore potentially a better representation of an average tissue sample and less dependant on sample location.

Additionally, when preparing test samples for tensile testing, it was noted that the inside and outside layers of tissue are adhered very loosely with thin connective tissue. An investigation was launched to determine how the material properties of the inner and outer layers of stomach tissue differed. Quite surprisingly, the inner mucosal layers of the stomach tissue were found to be slightly different and stronger than the outer muscular layers. Even still, they were both relatively similar and until the interaction between the
layers can be fully quantified, design engineers should continue to consider the gastric tissue in its bulk form to be a homogeneous tissue for device development purposes.

Largely due to the clear homogeneity of the material, testing the silicone tissue substitute proved to be much more straightforward. There were not the difficulties and uncertainties when slicing a test sample, matching inner and outer layers, nor about twisting the layers during fixturing. The one problem that was encountered, however, was the tensile testing machine did not have sufficient travel to completely break the silicone. Smaller samples were cut in an attempt to increase stress levels, but this only resulted in higher error and more variability in reported data. Even still, enough data was collected over a large enough strain to facilitate the needs of the FEA portion of this research.

Finally, despite the differences discussed above between the testing methods of Gregersen, Zhao, and Egorov to those used by the author, and the repeatability of data shown by the tensile testing completed at the University of Minnesota – the material properties established through this experimentation are trusted to be the most accurate portrayal of human gastric known to the field.

3. Finite Element Analysis (FEA)

Introduction

The previous section detailing the material properties of human gastric tissue provided the necessary information to allow a finite element analysis to be completed. Tissue properties are one of many parameters that must be specified when performing such computer simulations. These inputs must closely match actual samples in order for the results to be meaningful. Using a quarter-symmetry segment, the gastric tissue went through a series of simulated balloon dilations to examine the effects of radial expansion where the balloon is assumed to be infinitely long in relation to the relatively thin tissue cross-section. From this, a safe balloon and initial incision size can be determined for optimized device efficacy and an optimum surgical intervention and healing experience.
3.1 Background on FEA

Finite Element Analysis (FEA) is a computationally intensive method of determining strains and stresses in items that are difficult – if not impossible – to calculate with other methods with a high degree of accuracy. In a standard static state stress problem when determining the stress in a cantilever beam, the beam model might be idealized and theoretical values achieved. With FEA, the exact shape and dimensions can be used, true loading scenarios taken into account more accurately, and even dynamic loads and responses can be calculated for almost any object. FEA can be one of the most useful tools engineers can use to shorten product development and optimize product functionality by allowing multiple rapid alterations in both device shape and functionality and the loading characteristics it may see. Since very simple shapes can become extremely large calculations, FEA is almost exclusively performed by computer simulation. Even still, all of the computer programs utilizing FEA are based on the same fundamental theories of iteratively calculating the interaction between adjacent nodes and elements to reach a solution – or convergence. Appendix A covers the fundamental theory on calculating these interactions.

There are several main features that will determine the resulting accuracy of a simulation: material properties, geometry, part mesh, boundary conditions, and initial conditions. Collectively, these are generally known as the assumptions. In the case of assemblies, another assumption – interaction between parts – must also be accounted for. These assumptions affect the result in many ways depending on how the user applies them. The higher the degree accuracy of these assumptions with the actual operating conditions will yield a more accurate result. However, if the simulation perfectly duplicates the physical model, the resulting computations may take prohibitively long to complete. Though these solutions will likely be very accurate, the time cost is very high, therefore some of the many assumptions need to be modified to generate an accurate solution while eliminating unnecessary computation time.

It is wise to use material properties known to the literature in order to get best results. In the case of most metals, ceramics, and polymers, these material properties have been
established over time by many independent experimental procedures to yield accepted
standards. These properties most commonly reported and used for most elastic
deformation problems are: modulus of elasticity, Poisson’s Ratio, and density. More
complex simulations involving heat transfer, electric, acoustic, and damage models can
be performed using their respective properties and material constants. If a material
constant is not available in the literature, one must experimentally measure the required
material property firsthand.

Often, geometric simplifications can be used to expedite simulation time without
affecting the resulting accuracy of the solution. One of the first simplifications looked for
is symmetry. Is it possible for a circular object to be simulated by using only ¼ of the
whole part? Can a rectangular part be cut in half to save simulation time? Can an item be
simulated as two-dimensional rather than the full three-dimensional geometry? Many
times, model symmetry can be used to speed up the processing time for initial
simulations and a full-geometry run used to validate final results.

Another area of importance for the correct calculation of stresses and strains involves the
part mesh. A mesh is a combination of nodes and connecting elements discretizing two
and three dimensional geometry necessary for the finite element analysis program to
perform a simulation. There are four portions of a mesh that affect the results: meshing
technique, mesh density, element size, and element shape. There are several meshing
techniques which can be used to create elements. Free meshing uses no predefined
patterns and the resulting pattern is impossible to predict. This can be problematic
because there is no way to predict where the program will define the nodes, elements, and
resulting mesh, it resultantly can appear quite random and ineffective. Many times free
meshing is used as an initial test when worst-stressed areas are difficult to predict.
Subsequent testing generally uses another form of meshing to obtain more accurate
results. Swept meshing is preferred, as the user gives specified edges a number or density
of elements and this number is swept across a path to create a very ordered mesh. The
user completely controls the location and number of elements so areas of high importance
can have higher density, and lower importance low density. Similarly controllable,
structured meshing uses predefined meshed shapes and apply these to correspondingly shaped areas of the part to create a very ordered mesh. Finally, mapped meshing and virtual topology are methods to re-mesh areas that either require a more detailed or ordered mesh or more sparsely mesh areas of low importance yet unintentionally has multiple bad elements due to tiny faces and edges. Parts can be partitioned to allow for regions of different meshing styles based on geometry and relative importance of different areas.

As already eluded to, the density of the mesh can also impact the results. A higher density is required in areas of high strain and conversely low density in low strain areas. A fewer number of elements assists in reducing the computation time for the program to reach convergence, yet not at the expense of accuracy. It is desired to have at a minimum one element per gradation on the final result; if there are several gradations per element this implies large amounts of interpolation and the result can be of questionable accuracy. Directly related to element density and related to meshing technique is the element size. The finite element analysis program more accurately calculates each element if they are relatively even in size and shape. Largely skewed elements or several very small elements in areas of large element size can cause calculation problems for the program. Also, smaller elements mean more elements which increases computation time. Therefore, it is advisable to only use small elements in areas of high stress and importance and more sparsely populate areas of lesser importance and stress.

Of final importance to the mesh is the shape and type of the element. Elements can be either hexahedral or tetrahedral. Hex elements are usually used when the shape is meshed using swept meshing, mapped meshing, or virtual topography. Tetrahedral mesh elements are created when swept meshing is used, as a cubic shape is generated when nodes seeded along edges are propagated along a path in three dimensions. While the shape of element is determined by the meshing technique, the type of element is selected independently using mesh controls. Various different types of elements can be assigned to different regions of the model. Controls such as linear or geometric interpolation, hourglass and
stiffness control and standard or explicit analysis can be altered parametrically to study the effect of each on the result.

Each of the variables in meshing and part can and should be altered during the course of simulations to discover the result sensitivity in each. For example, mesh density is initially very coarse to allow for fast simulation time. This allows for efficient parametric studies by gradually increasing mesh density and subsequently simulation time until the result becomes stable. Similar studies can be performed altering the mesh density and element types and analyzing how the simulation results change. If the result changes, it must also be analyzed if the change means a more or less accurate result. Typically, experimental verification ensues to validate the assumptions and computer simulation accuracy.

Two more features needed to fully constrain the model are the initial conditions (IC’s) and boundary conditions (BC’s). IC’s are essentially the loads placed on the object, or anything that induces and change in response from the initial state. These loads can include: concentrated forces, body forces, surface tractions such as pressure, shear, or temperature. During analysis, these loads can be applied in a single step, ramped amplitude, or in any user defined function of load over the given time step. Under such variables, literally any possible loading condition replicating actual performance parameters is feasible. BC’s are very similar to IC’s but instead of body forces, boundary conditions work on the boundary or act as the steady state condition of the physical object. Examples of BC’s are symmetry planes, fixed or pinned points, planes, or edges in translation and/or rotation, or initial displacements, rotations, velocities, or accelerations designed to be the steady state “normal” position or state of the object. Together, the IC’s and BC’s act together as both fixation and active forces that are of interest in analyzing stresses and strains of objects or assemblies that can be used to determine success or failure under those loading conditions.

The process to perform a finite element analysis using computer simulation is relatively straightforward. The geometry must first be either imported as a *.iges file or drawn similar to creating any part in CAD packages such as SolidWorks or ProEngineer. Care
must be given in creating parts not to oversimplify parts by giving sharp edges where small radii actually exist thereby creating artificial stress risers. Next, material properties are defined and assigned to each object in the simulation. The part is meshed and loads and boundary conditions applied. After that, the desired output metric is selected and convergence criteria. A higher convergence criteria gives a more accurate result, but takes longer. With a very high degree of convergence there exists a possibility that convergence is never reached so care must be exercised when selecting this criteria. Finally, the results are post-processed and analyzed critically. This step is perhaps the most important. Most commonly, the information is displayed graphically for ease of interpretation. The engineer uses a critical eye to scrutinize the figure for inconsistencies in expected results and proper geometric orientation.

The use of FEA has revolutionized the design and development of new devices. The ability of design engineers to draw a part, test it, and make changes all from their desk within a few hours greatly reduces the time necessary to reach project completion. Additionally, an untold number of resources (time, money, man-hours, and materials) are saved because the number of prototype iterations and the work involved producing and testing is nearly eliminated. Finally, because the device is analyzed via computer simulation, the success threshold can be quickly determined for optimum device performance. If a device fails, the designer can know by how much, and alternatively if it is successful. The fine line between success and failure is discovered and the device tailored for a proper safety factor leading to an optimum performing, safe device.

Computer simulation has the ability to assist design engineers in optimizing their device by allowing users to fine-tune designs for maximum safety and efficacy in their working environments. This is particularly useful in biomedical device design where actual device testing in humans is unachievable in most cases due to FDA regulations, and animal model testing can be both time intensive to get IRB approval and monetarily costly. The device under development for this dissertation is a prime example of a surgical tool where testing and evaluation can easily be performed via finite element analysis in an
effort to save monetary and animal resources which to shorten the timeline between design iterations.

### 3.2 Setting up the Finite Element Model

Creating a model to accurately and efficiently compute the finite element analysis depends entirely on the assumptions implemented during preprocessing of the computer model. The previously described assumptions gave an overview, while the following discussion extrapolates on these topics and apply them directly to this research.

#### 3.2.1 Material Model

Even though both materials – human gastric tissue and silicone sheet – are fully characterized by a uniaxial tension test, this alone is not sufficient to perform a finite element analysis. When defining the material in ABAQUS, various parameters such as density, Poisson’s ratio, and elastic properties are entered which help drive internal calculations. Elastic and plastic properties are perhaps the most important of the material properties, because they are perhaps the most important metric in how an element deforms under stress. Several methods to define elastic properties are available in ABAQUS, and care should be taken to select the proper model. Several different material models are described and used in the simulation to determine the most appropriate method of defining both human gastric tissue and the silicone material phantom.

##### 3.2.1.1 Human Gastric Tissue

For an elastic material, it must be determined whether the material is hyperfoam, hypoelastic, porous elastic, linearly elastic, hyperelastic, or viscoelastic. A hyperfoam material is one that is highly compressible and returns to its native geometry.\(^{211}\) Compression was not tested in the stomach tissue, however the strain seen at maximum stress is relatively low, so a hyperfoam material assumption would be incorrect. Hypoelastic defines a material that is non-linear and is defined by a function of stress vs. strain.\(^{212}\) Additionally, when unloaded, it will not return to its native geometry – so this is
also an incorrect material assumption. A porous elastic material is both porous and linearly elastic, neither of which are accurate assumptions for gastric tissue. Linear elastic is also not a correct material model, because it can be seen from early tissue tests (Figure 2-29) that the gastric tissue undergoes an area of curvature before reaching the linear portion of the curve. This disqualifies linear elastic as a material model, and only two remain: viscoelastic or hyperelastic.

Between these last two material property assumptions, there seems to be some discrepancy as what the tissue actually is, and how to model it. Sibler et al. from the Center of Biomedical Engineering at Frankfurt University believe biological tissue is viscoelastic. This would mean the tissue properties are strain-rate dependent. This would seem an adequate assumption given the large differences between reported material properties between those produced for this dissertation and those reported previously in the literature. Even still, most researchers, Sibler et al. included, use a hyperelastic material model as was established by Fung. This could be because the strain rate applied during simulation closely represents strain rate during testing and simplification of finding and entering material property constants. Hyperelastic materials are nonlinear, and therefore the stress at any point is a function of the strain, and this function must be defined and entered.

There are multiple theories on modeling hyperelasticity, and each one applies to different types of materials and loading scenarios. Table 3-1 shows several different materials typically used for different types of rubber and their hyperelastic model. From this figure it can be seen that one rubber is not the same as the next, which can be extrapolated to say that not all biological materials will use the same hyperelastic model also. Several models that have been employed for biological tissues are shown in Table 3-2. It can be seen that even for the same material, breast tissue for example, different hyperelastic models are used depending on the analysis type, Arruda-Boyce or Mooney-Rivlin.
Table 3-1: Material model assumption for different types of rubber

<table>
<thead>
<tr>
<th>Material</th>
<th>Hyperelastic Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acrylate-butadiene rubber</td>
<td>Neo-Hookean</td>
</tr>
<tr>
<td>Chloroprene Rubber</td>
<td>Arruda-Boyce / Yeoh</td>
</tr>
<tr>
<td>Natural Rubber (55 pph CB)</td>
<td>Yeoh</td>
</tr>
<tr>
<td>Nitrile Rubber</td>
<td>Neo-Hookean</td>
</tr>
<tr>
<td>Silicon Rubber</td>
<td>Arruda-Boyce</td>
</tr>
<tr>
<td>Viton</td>
<td>Arruda-Boyce</td>
</tr>
</tbody>
</table>

Table 3-2: Selection of biological tissues and their associated hyperelastic models in the literature

<table>
<thead>
<tr>
<th>Tissue</th>
<th>Hyperelastic Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Human breast</td>
<td>Arruda-Boyce</td>
</tr>
<tr>
<td>Pig liver</td>
<td>Neo-Hooke</td>
</tr>
<tr>
<td>Human liver</td>
<td>Mooney-Rivlin</td>
</tr>
<tr>
<td>Human breast</td>
<td>Mooney-Rivlin</td>
</tr>
<tr>
<td>Subcutaneous fat and muscle</td>
<td>Ogden</td>
</tr>
<tr>
<td>Pig liver</td>
<td>Ogden</td>
</tr>
<tr>
<td>Soft-tissue tumor</td>
<td>Second-order Polynomial</td>
</tr>
<tr>
<td>Soft-tissue tumor</td>
<td>Yeoh</td>
</tr>
</tbody>
</table>

The purpose for using different hyperelastic models is because each has the ability to match the experimental data closely for certain materials in a given strain range. The goal is to match the hyperelastic model best to the range of strain values expected during simulation, hence the reason to use different models for the same tissue. However, none of these models are able to accurately match experimental data over large strains for a large number of materials.

The simplest method to quickly analyze the material model and compare it to various hyperelastic models is to evaluate the material in a function inherent in ABAQUS. To evaluate, the experimental material stress-strain information is plotted along with any of the possible hyperelastic models. The best fit over the strain values of concern is then selected and used as the associated material model for subsequent simulations. The next
step is to define an appropriate set of strains for this simulation. Referring back to Figure 2-34, it may be inaccurate to include the entire data set as the possible strain values for the FEA. After a strain value of 0.304, the plot starts to decrease drastically; meaning that each subsequent change in strain results in a reduced stress value. This equates to irreversible damage being done on the tissue. Because the purpose of this FEA is to determine safe operating parameters of the device, if strains larger than those that correlate to maximum stress are seen, the tissue is breaking down this region is undesirable and can be eliminated for this modeling. The yield stress is found where the slope of the stress-strain becomes zero. The maximum strain is taken to be the value that corresponds to that yield stress, and the material model is truncated at that point. The first iteration of the material model is shown in Figure 3-1.

![Figure 3-1: Truncated material properties to be used for FEA](image)

In order to use the truncated model, the correct hyperelastic model must be selected from ABAQUS. Initially, all of the hyperelastic models from ABAQUS were selected for evaluation. Results were to be compared to eliminate those models that do not fit well. However, the evaluation failed to converge for Arruda-Boyce so this was excluded and evaluation was re-run. See Figure 3-2 for the results of this simulation. The goal is to have the hyperelastic model match the test data as closely as possible, so many can be eliminated quite easily: Van Der Waals; Reduced Polynomial N=1, 2, 3; Polynomial
N=1; and Ogden N=1, 2, 3. This method of evaluating the model and eliminating the worst-fit continued until only a few remained, Figure 3-3, of which Ogden N=6, and Marlow are the best-fit options.

Figure 3-2: Initial uniaxial hyperelastic material model evaluation
During analysis, both of these hyperelastic models were analyzed under identical conditions to see the difference in final plot. Due to the similarities in the plots, it became difficult to determine the most accurate hyperelastic model. Two factors aided in the determination that Marlow was the most appropriate hyperelastic model for ABAQUS to use. First, if there is only one set of test data (uniaxial, biaxial, planar, or volumetric test data), Ogden is known to be inaccurate in compression. Second, the Marlow model exactly reproduces the test data, and when only one set of test data is available is obviously the most accurate. So despite both evaluations being relatively similar, the Marlow model is determined to be the most accurate hyperelastic model for the truncated uniaxial tension gastric tissue data set.

The problem with the truncated material model is that it assumes that as soon as the yield stress has been reached the tissue fractures and is incapable of holding any load. This is typical of more classic fracture seen in materials such as a metal or ceramic, however given the stress-strain curves discussed in Chapter 2, the tissue continues to exhibit holding capabilities until complete failure and a return back to zero stress. During initial ABAQUS simulations, using the truncated material model caused errors in two different
ways. First, when strains are above the maximum defined, the model can error from excessively distorted elements. This causes the simulation to stop before the true end of the time step and predictions may be excessively conservative. Second, if this error does not occur, ABAQUS may extrapolate out from the defined curve in order to fit a material model to the strains encountered in the simulation. The latter error causes the stress values to be far greater than what is physically possible given the defined material model. Therefore, a “damage model” was explored in an attempt to more accurately define the tissue.

ABAQUS has several damage models inherent to the FEA code that can account for decreased strength after yield. There are damage models for metals of various types, composites, shear loading, surface imperfections, yet only one for rubber-type materials. This is called the Mullins Effect, and is used to apply instantaneous and irreversible stress softening to elastomer materials after maximum stress has been reached. Before this point in the calculation, the standard hyperelastic material model is used. The Mullins Effect damage model was included in addition to the hyperelastic material model, but unfortunately errors resulted that stopped the analysis from even starting. Furthermore, without knowing the exact method that the Mullins Effect uses to stress-soften (ignore elements, eliminate elements, reduce stiffness), an added variable of uncertainty was introduced. Clearly, a more easily understandable material model to account for the stress-softening must be used.

One rather simplistic method to account for the stress softening of the gastric tissue is to redefine the hyperelastic material model to include all strain values. In this embodiment, the stress at any given strain will be clearly defined via the complete material model. In order to most accurately use a full curve of the gastric tissue, a hyperelastic evaluation similar to the truncated model was performed using the full tensile-test data set, see Figure 3-4. Even without eliminating imprecise and/or overlapping plots it is clear to see that the only model that even remotely fits the test data is the Marlow hyperelastic model.
For both cases of the truncated or full material simulations, the best hyperelastic model is Marlow. Marlow is unique in that it can exactly parallel the test data. Even still, work was completed by Lin et al. who worked to develop a theoretical hyperelastic model which even more exactly simulates the material. A considerable amount of theoretical effort and the use of user-defined sub-routines to enable their new model to duplicate the data. While this theoretical work for a more exact fit is impressive, Figure 2-26 showed a large amount of variability in the data and therefore the effort to more exactly fit an exact curve to data with large standard deviations seemed ineffectual.

Using the full material model as the hyperelastic definition may have a drawback, however. From the full material model plot and from observations during tensile testing it is seen that after strains where stress-softening initiates, irreversible tissue damage has occurred. So, if the entire stress-strain data is input as a hyperelastic model without
accounting for this irreversibility the results may be inaccurate. The exact mechanism of
error was unclear and explored during FEA simulations. It was discovered that when
using the full Marlow material definition ABAQUS gave erroneously large stress levels
when the model underwent large strains. Stresses nearly 140% of the maximum
allowable as defined by the material model were discovered. Clearly, this shows an
inconsistency between the way the material model was thought to be used and the method
ABAQUS actually used the information.

Obviously, defining the hyperelastic material as the full stress-strain curve is flawed
because it assumes full reversibility after yield. Full reversibility is actually only
achievable up to the maximum stress, after that point irreversible tissue damage occurs.
In order to account for both the fully elastic and plastic regions, the material model was
altered to a two-part model which included the full elastic curve and a plastic material
model for the stress-softening region. The plastic material model utilized the same stress-
strain data as the full model, but plastic strain starting at zero began at the yield stress and
the new table was defined. Therefore, for all strains greater than 0.304, both plastic and
elastic material definitions were layered which created a material with two possible
properties at any given strain. This material information was coded into and ABAQUS
simulation to test the validity of such property definitions. The result appeared quite
regular, with a maximum stress value within the allowable limits from the material data,
yet it failed due to excessively distorted elements. Without a clear reason to discredit this
strategy, the third method of describing the gastric tissue was analyzed and compared.

The third method of defining the gastric tissue was to combine both the truncated elastic
and stress-softening plastic properties separately. In order to account for both the fully
elastic and plastic regions, the material model included the truncated hyperelastic model
up to the yield stress, and a plastic model for strains past yield. In this instance, the
material will only have one definition at any given strain, hopefully eliminating any
inconsistencies with the reporting of stress when after yield. Once again, this information
was coded into ABAQUS for a sample analysis to test for any instability in the material
model. However, the results furnished quite similar results to the previous material model
– except without the excessively distorted element error. Since the latter two material models both seemed to work equally well, expert advice was sought to determine the most appropriate method of defining plasticity – either in combination with the full or truncated elastic model. After discussions with an engineer from ABAQUS Central, it was determined the most accurate method to define the human gastric tissue given the uniaxial pull-test data available was to give a hyperelastic material model up to strain of 0.304 (yield), and plastic material model for strains above that. Combined, these two definitions most accurately capture both they hyperelastic and stress-softening nature seen in the tensile testing of human gastric tissue.

3.2.1.2 Silicone Tissue Substitute

In similar fashion to the human gastric tissue, the silicone tissue substitute must also be accurately defined within ABAQUS in order for the model to solve accurately. One major difference between modeling tissue and silicone is the assumption to model it as a hyperelastic material. Silicone, by definition, is hyperelastic. Also, the Ogden hyperelastic material model is typically used to express the mechanical behavior of silicone rubber.\textsuperscript{225,226} Even still, a closer look was given to the hyperelastic assumption for silicone to ensure the most accurate model was used.

The best-fit curve developed for the silicone tensile test data was loaded into ABAQUS and evaluated for the best hyperelastic model. Initially, all possible theories were included. Then, theories not closely matching the data were to be removed. However, due to the simplistic nature of the stress-strain curve, it would have been quite difficult to exclude any model because they all seemed to fit very well, see Figure 3-5. Since all models fit equally well, the Marlow hyperelastic model was chosen to be used for two reasons: 1) it is able to exactly duplicate the input test data, and 2) the Marlow model was used for gastric tissue. In an attempt to reduce sources of variation between models, the Marlow hyperelastic model will also be used for the silicone material.
3.2.2 Physical Model Simplifications

The physical model is perhaps one of the easiest portions of the analysis to greatly reduce computational intensity while maintaining extremely high levels of accuracy. The very first major simplification to be used is using only a small portion of the stomach rather than modeling the entire organ. The stomach wall is considered to be of infinite length in relation to the relatively small hole, so there is no use in modeling the entire organ when stresses and strains only in the immediate vicinity of the incision are of concern for this procedure. In this analysis, the general idea is to radially expand a small hole in the gastric wall, Figure 3-6 (A) to a diameter between 0mm – 30mm, Figure 3-6 (B). Several different initial geometric shapes will be investigated to determine stresses and strains in the material when expanded from various initial geometries. The hole will be expanded radially to achieve a circular hole through the tissue. Due to the radial expansion, it then becomes intuitive to use a circular external shape, rather than square, to allow for ease of using a cylindrical meshing technique later on. Furthermore, the modeling of expanding a circular defect in a circular object leads to a very simple assumption of using radial symmetry to simplify the model.
Radial symmetry assumes that the object under analysis presents with symmetry radially in some fashion. The most extreme case is where the stresses and strains are circumferentially uniform and consequently the stresses and strains are a direct function only of the radius. It is then possible to reduce the large three-dimensional problem to a 2-D radial projection of a plane perpendicular to the face of the tissue which intersects the center of the circle, represented by the dotted lines in Figure 3-7. The forces are then placed on the left edge of the rectangular radial cross-section and the resulting stresses are assumed to be equal for any radii for that simulation. Consequently, as a pressure is applied to the inner radius, this load is evenly spread circumferentially through the object only in a linear fashion.
However, this type of simplification can only be made when the radius is assumed to be infinitely large or both the inner and outer radii are very dimensionally close. This is not the case, though, since the force being applied to the ID is spread out through a much larger area of tissue. This extreme version of radial-symmetry is not accurate, but there is a simplification inherent to ABAQUS that is usable when the center ID is concentric to the OD – axisymmetric. This simplification can only be used in the conditions described: the entire model is symmetric about a center axis. For the simulation, a two-dimensional cross-section of one side of the axis is drawn similar to Figure 3-7. ABAQUS then proceeds with the calculation by extrapolating out to the full circle geometry, completing the simulation, the displaying the axisymmetric solution. Though very effective, the axisymmetric model is an inappropriate assumption when an ID non-concentric to the OD is used. This necessitates moving to the three-dimensional realm.

When a non-circular initial incision is used, care must be given to the orientation of said initial shape to attempt to still make use of symmetry planes. It is unlikely that the initial incision through the gastric wall will be perfectly circular, but rather some kind of an oval or slit. Analytically, the orientation of the slit does not matter, so it is best to place it in a way that makes the rest of the plane symmetric. An oval or slit can be placed centered vertically, so the top half of the test circle of tissue is identical to the bottom half. Furthermore, it can be centered left-to-right so another half of the model can be removed. The resulting shape is called a quarter-symmetry model (Figure 3-8). The stresses and strains calculated for this shape can be mirrored over the x- and y-axis producing the full three-dimensional model.
This geometric simplification will reduce the computational complexity by the proportional amount of the model that is eliminated through symmetry. The initial simulations completed are those where a two-dimensional simplification can be made. The results from this analysis are used in order to determine approximate initial dimensions to test for both the linear and eccentric incision. However, the initial incision size is not the only variable which is determined through these geometric simplifications. The maximum expansion size is also altered to discover the material limits between a large enough incision to allow the device and scope to pass while still giving enough room for device manipulation and any organ/tissue extraction that might be necessary. The resulting compromise establishes the parameters not only for device design, but also recommendations for the surgeon in order for device efficacy.

### 3.2.3 Mesh

Meshing of both the 2D and 3D physical model is relatively straight forward. The previous section discussed several two- and three-dimensional models which must be meshed in an effort to obtain an accurate and timely solution. The models are quite regular in shape and have a very expected result – radial expansion of the initial incision. Because of these known features, free meshing was avoided as it works best as an initial test when reactions and most-stressed areas are unknown or difficult to predict. Instead,
the models use a seeded swept mesh to ensure high mesh density in areas of high stress, and low density in low stress areas. This swept mesh allows the computer to more efficiently calculate stresses due to the uniformity of elemental positions.

In order to properly mesh the two-dimensional axisymmetric model, a swept mesh was used in conjunction with a biased seed to allow for areas of higher mesh density where higher stresses are expected. The vertical axis is uniformly seeded, and the horizontal axis is biased towards the ID so smaller elements appear on the left. See Figure 3-9 for a sample showing the axisymmetric mesh. Care must be used when using this meshing technique. While it is desirable to have several elements per stress contour in the final plot, in an attempt to achieve these results the initial aspect ratio of the elements may become heavily skewed. If elements are skewed 10:1 with the height or width being significantly larger than the other the results are not as reliable, and the simulation may error-out. Therefore, the exact definition of the mesh is altered slightly after initial simulations.

![Figure 3-9: Axisymmetric mesh](image)

Meshing the three-dimensional figure is very similar to the axisymmetric model, using a swept mesh to ensure proper mesh density in high stress areas and low density in low stress areas. It has a uniform seed in the vertical axis and a biased seed along the horizontal axis with a higher mesh density towards the initial incision where higher stresses are expected, so the thickness appears two-dimensionally in Figure 3-10, (note the similarity to Figure 3-9). When a swept mesh is used, the mesh should be swept to follow the native geometry as closely as possible. This reduces the risk of creating
heavily skewed elements that result in errors during calculations. Therefore, instead of creating a blocked Cartesian mesh, a cylindrical coordinate mesh is used. The key to this mesh is to make sure the number of elements on the outer radius equal the number on the inner radius. This actually lends itself very nicely to the expected results of higher stresses on the inner radius because the nodes are much closer together on the ID thereby creating smaller elements. Along with a biased seed along the radial direction, elements of similar rectangular proportions are achievable in the entire model, Figure 3-11.

Even when the incision becomes a linear or circular slit instead of perfectly circular, the same principles of matching the number of nodes on the ID and OD must match. By changing the number of nodes on the circular and linear portions, the aspect ratio and skew of each element can be nearly equal. This is accomplished by partitioning the quarter-symmetry physical model into regions that correspond with the circular and linear
sections. Another partition also separates a region of higher density elements near the ID. The result is a very evenly seeded mesh which resembles the circular ID, yet has the increased complexity of a linear or circular slit, Figure 3-12.

![Partitioned physical model of linear slit and close-up showing various partitions](image)

**Figure 3-12: Partitioned physical model of linear slit and close-up showing various partitions**

Each of the meshes discussed were modified after initial computer simulations. This mesh refinement was performed for several reasons. First, there are instances where during calculations the mesh becomes too distorted to allow for accurate calculations and ABAQUS fails to converge. Various steps to modify the mesh to mitigate this risk along with using adaptive meshing can be used. In a standard simulation, the mesh is tied to the physical geometry. Adaptive meshing allows the mesh to be readjusted independent of the physical geometry. As elements become excessively distorted from the loads, ABAQUS readjusts the mesh and redefines the mesh mid-simulation to fix problem elements. In addition to distorted elements, another purpose for modifying the mesh is to allow for at least one elements per stress gradation. If the initial mesh has more than one stress gradation per element, ABAQUS has interpolated this solution the accuracy is questionable. Instead, at least one element should be present, but preferably more if possible.
### 3.2.4 Boundary Conditions and Initial Conditions

Boundary conditions (BC’s) and initial conditions (IC’s) or loads are some of the most dynamic variables in the finite element simulation. In this simulation, there are relatively few choices to select from for the BC’s. The same basic BC’s were used for the axisymmetric and three-dimensional models. They essentially work to hold the tissue from moving when an external displacement is forced on the ID of the tissue.

The axisymmetric model really has very few BC’s to worry about. The right-most edge is given an encastre BC (fixed in all translational and rotational degrees of freedom) to fix the outer edge of the model – thereby eliminating any possibility of bulk movement for the model. The bottom edge is free to allow the tissue to change thickness as needed during the simulation. Finally, the upper surface is given a Y-symmetry plane which effectively reduces the model to only half-thickness allowing for a faster computational time. See Figure 3-13 for these various boundary conditions. All results seen in the model could be mirrored about the Y-symmetry plane to recreate the full-thickness model.

![Figure 3-13: BC's of axisymmetric model](image)

In the quarter-symmetry model, the left edge is given an X-symmetry BC which tells the program to assume the model could be mirrored over the Y-axis with the same results. Elements and nodes can move vertically, but are constrained from moving horizontally. The bottom face is given an Y-symmetry BC in much the same fashion with the same results. The last symmetry plane implemented was a Z-symmetry plane. This creates a half-thickness model. Since the ID is where the load is applied, only one face remains for BC’s – the OD. This BC aims to hold the model in place from gross movement. The simplest way to do this is to constrain the outer edge radially, and fully fix just one point. The single point fixation will hold the entire model in place, while the radial constraint
will hold a constant OD. Though the FEA aims to mimic the actual loading environment, thought must also be given to the eventual experimental validation and use BC’s that are feasible to replicate easily. The BC just described, though a valid FEA constraint, would not be repeatable in the lab. Instead, the entire OD is given the fully encastre BC simulating fixing a piece of tissue in a circle of known radius. Refer to Figure 3-14 for pictorial representations of the BC’s.

**Figure 3-14: 3D model used in FEA balloon expansion of gastric tissue**

The purpose of this finite element analysis is to simulate a radial expansion of a small incision through the gastric tissue. The load is simulated as closely as possible to the radially expanding balloon. One method of doing this is through a pressure-expansion function. During surgery, a non-compliant balloon would be filled with air to achieve the expansion necessary to allow the passage of an endoscope into the peritoneal cavity. Modeling the non-compliant balloon is an incredibly difficult task attempting to uncurl the multiple folds of the balloon through the pneumatic pressure. Therefore, a
simplification was made to instead directly apply the pressure to the tissue itself. The reasoning behind this is as follows:

A representative operating pressure of the expansion balloon is selected, say 30 psi. This pressure is applied to the tissue ID and the resulting deformation analyzed. If the tissue does not expand to the desired final diameter (between 25mm – 30mm), then it is assumed that a balloon designed to 30 psi would not be able to expand the tissue adequately and the ID increased. If the simulation was able to fully reach convergence, then the initial ID was too large and was decreased to find the limit at the given pressure. This type of solution gives the threshold ID for a given pressure. Alternatively, an ID can be specified and the pressure altered. In this manner, if adequate tissue deformation was reached at a given pressure, it was decreased until the final deformed diameter was unachievable. The final diameter and the pressure are compared to the desired balloon size and pressure and a conclusion drawn on the initial incision and balloon operating pressure. These two variables were altered until an adequate solution was discovered.

A second, more robust, method for expanding the ID is to prescribe a radial dimensional change to the physical model. Though this will only work with the axisymmetric model, prescribing a dimension change lends itself to a more stable solution. When solving the model for a pressure applied to the ID, convergence is difficult to reach because the computer must determine when the distortion is complete for the given load. This ambiguity on final deformation leads to unstable solutions and errors in calculations. By instead prescribing the exact desired deformed shape, the computations are limited to the strains and stresses seen in the tissue.

A third method for deforming the tissue to the desired final diameter is by pushing a second three-dimensional part into the tissue. The second part would have the same circular shape as the desired final ID, and have material properties of a very rigid material – such as steel. This method is computationally intense, however, because of complex contact calculations and stresses for this second part must also be calculated.
The final method of radially expanding an initial incision is similar to how cardiovascular stents are modeled – through the use of an expansion cylinder. In this type of analysis, a 2D deformable cylindrical shell is used to create contact with the tissue ID to force the dilation to the desired shape. The shell is not given typical material properties of Young’s modulus and Poisson’s ratio as the stress of this part is undesired; only the surface density is needed for contact definitions. In this method, the simulation is computationally simple because stress and strain is not calculated for a second part.

### 3.2.5 ABAQUS Standard vs. ABAQUS Explicit

ABAQUS has two methods of calculating any FEA simulation, either through the Standard FEA calculation method, or though an advanced Explicit calculation. ABAQUS Standard calculates the finite element model in the same fashion as discussed earlier – iterations of calculations are completed in order to reach a steady-state solution. This implicit calculation style solves for a true static equilibrium. ABAQUS Explicit, however, solves for a true dynamic equilibrium which is more efficient especially for three-dimensional problems involving contact and/or large deformations. Instead of solving iterative calculations to achieve convergence through criteria determining the allowable difference between iterations, explicit continues to calculate over a predefined time step. This is especially useful for observing changes during dynamic simulations such as impact, vibrations, or metal forming. However, the Explicit solver can be used for static problems of certain conditions too. Therefore, both ABAQUS Standard and Explicit are used to determine which solver is most effective.

There are really very few differences between defining Implicit and Explicit simulations. In an effort to hasten the process of FEA, the Implicit solver was attempted first to determine if an Explicit solution was warranted. Even though a variety of different BC’s and IC’s were attempted, convergence proved to be very difficult. When the load approached 1% of the desired 30psi pressure load the model failed to complete. Further investigation lead to the conclusion that the non-convergence was due to the implicit solver’s inability to account for excessive distortion in the model. In sheet metal forming operations, the Implicit solver fails to converge at the point where the metal begins to
Wrinkle. This is similar with the style of simulation being preformed here, except instead of metal, the tissue is potentially being “crimped” or compressed in large deformations. Additionally, an Implicit solution is 20 times more computationally expensive in this simulation over the Explicit solver. Subsequently, the explicit solver was used for the remainder of the work.

While ABAQUS Explicit is meant for dynamic problems, it also is able to reach convergence in problems like this one where the implicit solver can not. Defining an explicit simulation becomes a little more difficult than Implicit, and three main assumptions can lead to drastically different solutions: load rate, mass scaling, and adaptive meshing. These variables work to achieve the same result – help the simulation complete faster – but they work in different ways. Increasing the load rate reduces the time scale of the simulation. However, if the load is applied too quickly it can result in a high velocity impact instead of a realistic loading mechanism. Figure 3-15 shows a phenomenon called jetting where a tool impacts the bulk material too quickly, while Figure 3-16 shows a metal car door beam being deformed during impact, note the lack of structural response in the high velocity scenario. It is best to limit the impact velocity to less than 1% of the wave speed of the material being deformed. In tissues, the wave speed depends on the density of the tissue; though ultrasound physics assumes that in most soft tissues the wave speed is assumed to be the same as through water – approximately 1500 m/s.

![Figure 3-15: Effect of tool speed on deformed shape](image-url)
Mass scaling works to reduce computation time by scaling the density of the parts in the analysis. Increasing the density dampens the potential for vibrations during deformation and in turn reduces the number of increments needed to complete the simulation. This is completed through scaling the density of the deformed shape. The time to converge will increase by a factor of the square root of the scale factor. For this analysis type, a factor of $1 \times 10^5$ is used first, reducing by orders of magnitude until the result stabilizes from former to current scale factor. Figure 3-17 shows the deformation of a metal bar under pure tension. The largest scale factor yields an erroneous result, while the other two are nearly identical, though the center image completed five times quicker. Mass scaling can be problematic, however, because it is easy to create physical impossibility. Through mass scaling, one could create a gelatinous material like Jello, but with the density of steel!
Finally, adaptive meshing (ALE) is used in simulations where the native mesh undergoes extreme deformations that lead to highly distorted elements. In a normal simulation using a Lagrangian mesh, the elements move directly with the physical model. It is possible, especially in high strain problems, for the simulation to discontinue due to excessively distorted elements – completely negating the work to create a high quality mesh in the first place. When using ALE, the mesh is smoothed at regular intervals during the simulation. The mesh topology – number of elements and nodes and connectivity – is maintained, yet redefined to eliminate areas of high distortion. An example of standard Lagrangian and ALE meshing is shown in Figure 3-18, and the resulting change in mesh during simulation is seen in Figure 3-19.

![Difference between standard (Lagrangian) meshing and adaptive meshing (ALE)](image)

**Figure 3-18: Difference between standard (Lagrangian) meshing and adaptive meshing (ALE)**

![Effect of adaptive meshing on deformed object during simulation](image)

**Figure 3-19: Effect of adaptive meshing on deformed object during simulation**
Throughout the Explicit FEA simulations performed on balloon expansion of human gastric tissue, all three of these Explicit simplifications were used with varying degrees of success. Their exact usage will be discussed in the following sections detailing the simulations of gastric tissue compared to the polymer test material.

### 3.3 Axisymmetric Analysis

The axisymmetric simplification method was used to reduce the three-dimensional geometry down to a two-dimensional projection of a radial plane. During the computational process, the projection is revolved about the axis and calculations performed as though the full three-dimensional object were used. Two different loading mechanisms were used: pressure and displacement. The gastric tissue was tested first, followed by the silicone tissue phantom. Both will be shown and compared for their relevance and accuracy to this FEA problem.

#### 3.3.1 Gastric Tissue

Human tissue provides a unique difficulty to the finite element analysis simulation procedure because the material properties make convergence with high strain analysis difficult. While there are several methods that can be employed in order to reign in the tissue model; many of the conclusions from the analysis are left to the judgment of the operator. For example, if a procedure does not reach convergence, this does not necessarily mean the model definition was incorrect. Perhaps the actual strain is above that defined in the material model. Perhaps the maximum diameter dilation was reached, but numerical instability occurred. Even still, several different types of simulations were performed in an attempt to fully capture the behavior of the gastric tissue.

##### 3.3.1.1 Pressure Controlled Deformation

In using the axisymmetric model, the first style of deformation simulated was to assign a pressure load to the ID of the model. In these analyses, the full material model was initially used. Using an initial incision of a hole with diameter 0.01m, the pressure was
placed directly on the tissue (without a balloon). Due to the instability of the simulation for this load, several orders of magnitude of pressure loads was attempted.

It is thought that during surgery, a dilation balloon would expand at a maximal load in the range of approximately 30psi; this converts to just over 200,000Pa. When this pressure was placed directly on the ID of the tissue, however, the simulation failed at a time step of 0.328 out of a finishing time step of 0.8 due to excessively distorted elements, Figure 3-20. This essentially means that the distortion the elements underwent due to the pressure load exceeded the maximum strain defined in the material model. When such instances occur, the bottom-left portion of the distorted shape in the ID close-up shows the obvious signs of high distortion,

![Figure 3-20: Close-up of distorted ID, pressure = 200,000Pa](image)

Subsequent simulations in which the pressure was varied aimed to locate the maximum pressure the ID of 0.01m could withstand within the material model. Several orders of magnitude of reduced pressure load were attempted in order to reach a pressure load which was able to converge. Starting at 2,000Pa, the pressure was increased until such instability occurred for non-convergence. In each simulation the initial ID was kept constant at 0.01m. Full non-convergence was reached at a pressure of 55,000 Pa (7.98psi), Figure 3-21. This equated to a final expanded diameter of 0.0149m.
In an attempt to ensure that the simplifications made to the model do not inadvertently alter the results or deformed geometry in any way, a simulation was run where the Y-symmetry plane was removed (refer back to Figure 3-13). A symmetry plane in the center-line effectively stabilizes the model from any potential buckling. With a long, thin section of soft material, even light loads can lead to buckling. To check this potential failure mode, a model was analyzed with the symmetry plane removed and full thickness restored. The same testing technique of increasing pressure until non-convergence was used. Maximum pressure was found to be the same as the above Y-symmetric model, 55,000 Pa with a final diameter of .01375m. The deformed shape with stress contour plot is shown in Figure 3-22.

Despite the apparent success in the pressure-controlled simulation, this style of analysis is inherently unstable because of the tissue material model. The stress-strain graph of the gastric tissue tensile testing is quite irregular – closely resembling a bell curve – by starting and finishing at a stress of zero. Therefore, when strains exceed when the tissue yields, instead of breaking completely it strain softens. As strain continues to increase, the stress decreases. In terms of a force-prescribed simulation, strain softening equates to
numerical instability. Because a force is prescribed, the model is responding to that force until no more displacement can be achieved. When the force creates strains past the yield, the material will continue to yield indefinitely, thereby leading to an inability to accurately complete the simulation and therefore rendering it unstable. While this type of simulation could be considered beneficial in some regards – the point at which yield and tissue damage can be determined – the stability issues defeat the ability in gaining a full understanding of the deformation process. Instead, a displacement controlled simulation in which the deformed geometry is prescribed by the deformation instead of the result of the load is a far more robust method of solving this analysis.

### 3.3.1.2 Displacement Controlled Deformation

The first step in the displacement controlled deformation is to determine the relative amount of expansion to be expected from the gastric tissue during a radial expansion. As a starting point for this, initial simulations were modeled with a 10mm ID, which was represented by a 5mm radius through the axisymmetric simplification. In order to begin the process of testing the magnitude of displacement possible, a simple calculation was performed using the strain at yield stress (shown to be 0.304 in chapter 2.2.2). Expanding a cylindrical balloon will compress the tissue radially, but stretch circumferentially. The area of maximum strain will be the area closest to the balloon – the ID. Combining these two facts leads to the realization that the deformed circumference should be 30.4% larger than the initial undeformed ID, Equation 3-1. Rearranging the equation, the allowable radial displacement (\(disp\)) can be calculated from the change in circumference in terms of the undeformed initial radius (\(r_i\)), Equation 3-2.

\[
C_f = 1.304 \times C_i \quad \text{Equation 3-1}
\]

\[
\text{disp} = 0.304 \times r_i \quad \text{Equation 3-2}
\]

Solving Equation 3-2 for \(ri=0.005\) gives a solution: \(disp=0.00152\). Inputting these values into ABAQUS resulted in surprisingly accurate results, Figure 3-23. The expected value maximum stress was seen at the ID where it was expected. As expected, stress values
were at yield at the interior diameter, as the displacement was calculated from strains correlating to max stress. Despite this success, further simulations are needed to find out how much larger the deformation can undergo before complete failure. Also, the compressive nature of the deformation adds to the complexity of the simulation and a higher displacement may evoke more compressive responses. Even still, observing the stress level at the first displacement gave a good starting place for subsequent simulations.

The difficult question to answer, however, was what level of deformation that is acceptable. Looking at Figure 3-23, the stress level was highest at the interior diameter. The response to a larger strain, however, may produce a far different result. As previously described, when the strain level increases past yield, the tissue transitions into the plastic region of the material model the stress level actually decreases with increasing strain. Any material in the plastic region of the material model is considered irreversibly damaged. As the displacement becomes exceedingly large, the plastically deformed region near the ID will also become sizeable. This region of plastic deformation was previously expressed should stay minimal at most. Some plastic deformation at the ID is acceptable, however, because there exists a boundary layer which would already be damaged by the electrosurgical needle knife. When the knife cuts through the tissue it is essentially thermally damaging and vaporizing parts of the tissue. After the cut is complete, a thin layer of irreversibly thermally damaged tissue lines the edge. Depending on the setting on the electrosurgical device, thermal damage can be between 1mm – 6mm, with damage from cutting in the 1mm – 4mm range depending on variables.\(^{229,230}\)

This FEA simulation was able to take advantage of the damaged tissue nearest the ID by allowing this boundary layer to surpass the elastic material model because it is already

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**Figure 3-23: Radius 0.005m, displacement 0.00152m**
damaged and therefore can mechanically damaged as well without significant surgical differences.

In similar fashion to the pressure controlled displacement, an range of displacements were tested in an attempt to narrow down the critical degree of deformation a 5 mm initial radius can safely undergo. Using the axisymmetric model with a half-thickness Y-symmetry plane, the maximum dilation was found to be 0.00288m – a 57.6% increase of the initial radius, Figure 3-24. When extrapolated into the full model, this means a 0.01m initial incision can be balloon dilated to a final diameter of 0.01576m.

![Figure 3-24: Radius 0.005m, displacement 0.00288m](image)

There are two unique things about the deformed contour plot that require explanations. First, the worst stressed area is away from the ID. This is an artifact of the material model. Due to the material model behaving like a “bell curve,” after the yield stress has been achieved, increasingly higher strains equal lower stresses. Therefore, although the ID may have a higher strain, it may be the worst stressed. The area to the left of the max stressed area is actually in the plastically deformed region and can be considered to have sustained irreversible damage. The plastic strain contour plot is seen in Figure 3-25. Notice how the areas of plastic strain correlate to the areas left of the max stressed area in Figure 3-24. This tissue has been plastically deformed and some of the tissue fibers have torn.
Second, the shape of the deformed plot shows mushrooming to the left of the max stressed area. This was not seen when the strain did not surpass the maximum reversible level, such as in Figure 3-23. The mushrooming deformation is a product of the material definition and the increased displacement. This is because when the simulation pushes the strain at the ID past yield, the simulation effectively becomes a softer material in front of a harder material. So, the softer material deforms and dissipates energy before energy is transferred to the ‘harder’ material creating the mushroomed shape nearest the ID. Also, the plastic deformation region is approximately 2.17 mm thick, and is acceptable since this area is well within the thickness of thermal damage from the needle knife. Therefore, despite the deformed shape appearing non-intuitive at first glance when remembering Figure 3-23, the Von Mises Stress and plastic strain contour plots show quite explainable and acceptable results.

First described in relation to the pressure-controlled deformation, using a Z-axis half-symmetry boundary condition may inadvertently stabilize the displacement controlled deformation from potential buckling. To test this, the BC was removed which re-established full thickness. Next, simulations similar to the half-thickness model were performed to find the critical displacement. As expected, the critical displacement for a radius of 0.005m was not a singular value, but a range of values where instability occurred due to the buckling phenomenon. The onset of this instability occurred at a displacement value of 0.00283m. Figure 3-26 (A) shows this buckled deformation and compares it to a displacement of 0.0282m where the last stable deformation was seen. The mesh was removed for easier visualization of the stress contours.
Figure 3-26: Stable displacement = 0.00282m (top), and buckling displacement = 0.00283m (bottom)

Shown more closely in Figure 3-27, the ID of the tissue post-buckling shows a far more pronounced degree of deformation due to the movement of the interior edge perpendicular to the direction of displacement. This type of deformation became increasingly more severe as the displacement values increased, Figure 3-28. At a value of 0.00288 m, the model was unable to find any stable solutions and increasing displacements led to more excessively distorted plots due to buckling. Mesh was again removed for easier viewing of stress contours.

Figure 3-27: Close-up of ID of buckling displacement = 0.00283m
These simulations with the full thickness prove just how much a boundary condition can affect the outcome of the analysis. The deformed shape is more similar to what would be expected from large displacements from small initial incisions. Buckling and instability occurred before the actual limits of the material. Even still, when looking at the numerical values of the full-thickness displacements, it shows there is a range of values where buckling may occur (between 0.00283m and 0.00288m). Past the top end, and buckling will always occur; below the bottom end of the range it will not. Coincidentally, the top end of this transition zone matches the limit of deformation when the half-thickness model is analyzed. These collinear results lead to the realization that further analyses can be performed with the Z-symmetry half-thickness assumption in order to decrease computational time and more easily define the limit of the materials during this deformation process.

While finding the maximum diameter a hole of 10mm can be expanded was useful for dialing in the FEA process, it is far more useful to instead find out the minimal size hole needed in order to expand out to a desired final diameter. In this case, the final size must be determined first, and then one needs to balance the initial ID and deformation to match. Looking back at the literature, the maximum size object that will fit through the larynx is .020m. It therefore seems logical to use this as a desired final expanded diameter as it seems unnecessary to dilate any larger than needed. However, it is possible that future surgical procedures may construct some type of mechanism within the body for a NOTES intervention, and therefore a larger expanded hole may be needed. A second final diameter of .025m was chosen.
The process to find the minimal size hole for maximal dilation proceeded as a trial-and-error decaying oscillatory method where both the ID and displacement were changed at the same time in order to maintain the desired final diameter. With 20mm as the desired expanded diameter, trials began with a very large initial ID and small displacement to ensure proper completion of the analysis. In half-millimeter increments, the initial ID was reduced and displacement increased until the threshold of analysis instability was crossed. Next, in 0.0001m increments, the space between the last complete and first incomplete analysis was explored to refine the solution space and narrow down the solutions. When using the Z-symmetry half-thickness simplification, the initial incision size was found to be 0.0065m with a 0.0035m displacement, Figure 3-29. When the Z-symmetry was removed and full-thickness restored, the parameters of the solution actually changed very little. Both the ID and displacement were altered by only 0.0001m to 0.0066m and 0.0034m respectively, Figure 3-30.

![Figure 3-29: Von Mises stress contour plot, ID=.0065m, displacement=.0035m](image)

![Figure 3-30: Von Mises stress contour plot, full thickness, ID=.0066m, displacement=.0034m](image)

The same process to narrow down the operating parameters of the initial incision size and the displacement were used when modeling a 25mm maximum expanded hole. In this instance, it was interesting to note that there was no difference between the ID and displacement between the model which used the Z-symmetry plane and the one that did
not. Both had an initial ID or 0.0083m, and a displacement of 0.0042m, Figure 3-31 and Figure 3-32.

The reason for the decreasing amount of discrepancy between the displacements and the unstable buckling behavior in the models which did and did not use Z-symmetry plane may actually have two possible causes – one an artifact of the simulation and one physical. When modeling the current analysis, assumptions were made about the size of the model to be used. It was improbable to use the entire stomach – far too much computation would be used for much of the model that would be inconsequential to the desired area of focus. Instead, a finite area assumed to be flat was isolated from the rest of the tissue. For each of the analyses, the larger area of tissue remained the same while the initial ID continued to become larger for subsequent simulations. It was seen in Figure 3-26 the tissue surpassed stable deformation and began buckling. The phenomenon of buckling as it applies to standard beams is heavily dependant on the length of said beam, Equation 3-3. \( L_e \) is the equivalent length of the beam, and depends on the boundary conditions, Figure 3-33. In this case, the beam is free-fixed, therefore \( L_e = 2.1L \). A shorter beam (smaller \( L_e \)) will require a larger load to buckle than a longer one will. While the analysis clearly does not simulate a beam, the same theory very roughly may apply – a smaller distance between the ID and outer edge of the model may
lead to a more stable solution where buckling may be concerned. Since each analysis used the same OD to the tissue model, this may be inadvertently causing simulations of larger initial diameters to be artificially stable.

\[ P_{cr} = \frac{\pi^2 F \cdot I}{L_e^2} \]

Equation 3-3

The other possibility for reduced instability and buckling with larger initial ID’s could merely be a function of the physical dimensions of the deformation. It was clear to see as the ID increased, the instability decreased. Furthermore, as the ID increased, the displacement decreased– expressed as a percent of the ID, Table 3-3.

<table>
<thead>
<tr>
<th>ID (mm)</th>
<th>Displacement (mm)</th>
<th>Percent Change</th>
<th>Initial area (mm²)</th>
<th>Displaced area (mm²)</th>
<th>Percent Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.0</td>
<td>2.88</td>
<td>57.60%</td>
<td>78.5398</td>
<td>116.535</td>
<td>148.38%</td>
</tr>
<tr>
<td>6.5</td>
<td>3.5</td>
<td>53.85%</td>
<td>132.732</td>
<td>181.427</td>
<td>136.69%</td>
</tr>
<tr>
<td>8.3</td>
<td>4.2</td>
<td>50.60%</td>
<td>216.424</td>
<td>274.45</td>
<td>126.81%</td>
</tr>
</tbody>
</table>

Table 3-3: Diameter change expressed as a percent of initial ID

It was explained earlier how the strains during the deformation process are a combination of radially compressive and concentrically tensile components. While the exact interactions of these two are not understood, the data is clear that not only the percent displacement decreases as the ID increases; the percent of the displaced area also
decreases. It could then be extrapolated that a smaller initial diameter undergoing radial
dilation has a higher degree of instability due to the necessity to relocate a larger percent
volume of tissue. An ID much larger than the ones explored during these analyses will
have a much smaller percent change in area meaning less tissue distorted, less volume to
displace, leading to a lower propensity for buckling to initiate.

3.3.2 Silicone Tissue Phantom

Building on the previous analysis, the simulation substituted the silicone material model
instead of the human gastric tissue. The largest difference between the two materials is
the lack of a plastic region for the silicone. Whether or not the material actually began to
yield is unclear, but according to the definitions established for the elastic/plastic regions
for the gastric tissue, the silicone stress-strain curve did not enter a stress-softening region
and therefore is considered to only be elastic. This is advantageous because a simpler
model will yield a more stable material in ABAQUS, allowing for easier calculations and
faster simulation times.

The physical model was defined nearly identical to the gastric model. The BC’s were a
fixed OD, Z-axis symmetry plane, and a displacement load to the right was placed on the
ID. The mesh also remained constant, with 10 elements along the thickness, and a
linearly biased mesh towards the ID along the radius. Rather than alter the ID and
displacement to find the best balance for the desired final ID, in anticipation for later
experimental analysis, only a single initial ID was used. The initial ID of the silicone was
selected to be 10mm, with displacements of 1, 2, 3, 4, and 5 mm. This equals final
deformed diameters of 12, 14, 16, 18, and 20mm. Figure 3-34 shows an example of the
def ormation of the final ID of 20mm.
Other deformed diameters showed very similar results, only differing in the stress levels from the reduced degree of deformation. Notice from this deformed plot, the similarity to the gastric tissue plots such as Figure 3-23. The areas of highest stress are located directly next to the ID and dissipated quickly moving along the radius. Next, this plot is compared to Figure 2-25. This plot shows the gastric tissue, but the area directly adjacent to the ID has mushroomed out. The silicone does not show this type of deformation. This difference is because the tissue crossed into the plastic deformation region, whereas the silicone is all elastic. Despite this difference, the two simulations are quite similar. The silicone material model was much simpler, from being able to physically observe the way the material behaves under loads the resulting FEA simulations seemed very plausible. The similarities of the gastric tissue analyses to the silicone analyses support the conclusion that the gastric tissue material model is correct in the axisymmetric model.

### 3.4 Three-Dimensional Analysis

To begin the three-dimensional analysis, the finalized dimensions of the analyses from the two-dimensional axisymmetric simulations were used. These allowed for verification of the axisymmetric assumptions, and extrapolate out to three-dimensions. Though most of the assumptions were identical from the axisymmetric model, the method for radially expanding the ID was significantly different.
3.4.1 Gastric Tissue

The simple ability to prescribe a dimension change on the inner diameter does not work directly for the three-dimensional model as it did for the axisymmetric model. Since dimension change must be prescribed in the Cartesian or cylindrical coordinate system, any change is input either into X, Y, Z, or R, \( \theta \), Z. To produce a uniform change in radius, only a cylindrical coordinate system would work. In order to define a dimension change in cylindrical coordinates, however, the model must also be constructed in cylindrical coordinates. Upon constructing the tissue model, an unexpected – though understandable – error occurred: X- and Y-axis symmetry planes cannot be defined in a model constructed in cylindrical coordinates. Various techniques of tie constraints and radial symmetry planes were attempted but none achieved the same desired results of the symmetry planes.

The next method attempted to create the radial deformation change was to use a deformable shell with surface density to push the ID out. A procedure quite similar to this is applied to the analysis of cardiac stents.\(^{232}\) However, in the case of stents, the shell is interacting with contact to another shell and it undergoes deformations much smaller than this example. The shell is given a radial deformation similar to the axisymmetric method and contact defined between the two parts. The shell elements were able to be given a radial displacement because the part was created with cylindrical coordinates and only interacts with the Cartesian coordinate part (tissue) through contact. During analysis, the model began quite regularly, but approximately 30% into the deformation the elements of the deformable shell underwent hourglassing – a phenomenon where adjacent individual elements buckle and essentially overlap– leading to excessively distorted elements in the tissue. Note in Figure 3-35 how the shell elements have buckled creating the hourglass shape. Hourglassing can be avoided by using second-order elements, but they are not available for shell elements. For small deformations, this proved to be a very effective method of dilating the tissue, but for larger displacements/forces the hourglassing prohibited the analysis from completing successfully.
Since the shell element to deform the ID did not work effectively, another method which was attempted was to create a solid “balloon” from a material significantly harder than the tissue – such as steel – created in the final deformed shape. The balloon was positioned away from the incision, and then pushed into the tissue until the deformed tissue matched the balloon, Figure 3-36. Assuming the simulation completed normally, the tissue would match the balloon – effectively creating the same deformation as if the balloon were inflated in place. A potential problem with this type of deformation is that if the simulation fails to complete fully, one is unable to extrapolate any information from these incomplete results because this dilation does not proceed normally. The unequal deformation distorts the edges first, and the center “catches up” only at the end of the time step.
Two different types of this deformation were attempted. In the first one, the balloon was positioned directly underneath the ID and moved in the Y-direction. This unfortunately did not converge as the place where contact initiated underwent extreme deformations unequal in the rest of the model, Figure 3-37 (A). In an attempt to reduce the impact from the initial contact, the second attempt initiated contact in two positions similar to Figure 3-36 and displaced equally in both the X- and Y- axis, see Figure 3-37 (B).

Figure 3-37: Steel balloon dilation; vertical displacement (left), 45° displacement (right)
Because it seemed as though for the simulation did not finish normally for a hard “balloon” moving into the dilation space, another three-dimensional FEA attempt was made by instead using a cone-shaped tapered object to penetrate the tissue. Once again, the material of the cone will be similar to steel – much more dense and rigid than the softer biological matter. Initially dimensioned to match the un-deformed ID and positioned perpendicular to the tissue plane, during the simulation it will move further into the tissue forcing the tissue to conform to the expanding diameter of the cone. Additionally, while the tissue will not be expanding exactly at the same rate across the diameter, the taper of the cone is slight enough to have rather minimal impact. This deformation more closely represents an actual dilation because it is seeing gradually increasing central diameter change; therefore intermediate results during the simulation are useful for discussion. Even still, since the movement of the cone was perpendicular to the direction of dilation, the tissue distorted excessively in an unexpected manner Figure 3-38, and this simulation did not produce reliable results.

The previous three attempts at a three-dimensional dilation of the gastric tissue using a rigid object all point to instability within the material model. Each of the simulations
show maximum stress levels at nearly the same level – between 1.641e+05 Pa and 1.690e+05 Pa – when the simulation stopped. This is important because the maximum stress level in the elastic material definition is 1.697e+05 Pa. It seems to reason that the transition from the elastic to plastic portions of the material model using the Marlow model causes instability. When the elastic model was redefined from the truncated portion to the full stress-strain plot, the same errors occurred.

To overcome the instability problems, the material assumption was re-evaluated using the axisymmetric model – which was known to be stable. The axisymmetric model of initial ID=8.3mm with a 4.2mm dilation (equal to final ID of 25mm) was used. Using the same material data of the truncated elastic model, the hyperelastic assumption was and the simulation re-run. This was performed for each of the possible hyperelastic models. The deformed plots were compared to the known-accurate Marlow model for similarities in maximum strain and shape. The following models were found to show nearly identical results: Ogden N=1, 2; Reduced Polynomial N=1 (Neo Hooke), 2, 3 (Yeoh), 4, 5, 6. Each of these was then attempted in the 3D model shown in Figure 3-37 (B), an all but the Neo Hooke model showed similar convergence difficulties. This simulation, however, was able to complete fully, (Figure 3-39).
Figure 3-39: Deformed plot of initial ID=16.6mm, final ID=25mm, Neo Hookean material model

Though the model completed, there are several problems. First, the level of stresses seen here are far below the expected results of 1.697e+05Pa. The maximum strain from the Neo Hooke model is only 21.5% of that seen in the Marlow model. When this was examined a bit closer, it was found that despite the similarities in the axisymmetric model material analysis, the Neo Hooke assumption shows a strikingly different stress-strain curve, (Figure 3-40). However, this shows a very important consideration when using axisymmetric vs. 3D models of the same problem: the axisymmetric assumption puts enough stability on the model to overcome instabilities in the material model. In this case, not only was the material model slightly unstable, but the additional complexity of the elastic/plastic property definitions added to the inability of the three-dimensional model to solve fully.
The analysis of the three-dimensional model using gastric tissue reached a critical juncture. After attempting multiple solving techniques, with multiple material strain-energy models, it was determined that the current material model was too unstable to continue. A more stable material might have been achieved by using more testing methods: biaxial and compression. This was not possible at this time, however. Therefore, in order to answer the remaining question of a non-circular initial incision, further analysis continued with the silicone material. While this does not solve the goal of determining the exact incision size necessary for safe passage through the gastric wall for the prototype, relative trends in areas of high and low stress and peak values can still be compared and extrapolated to make conclusions for native stomach tissue.

### 3.4.2 Silicone Tissue Phantom

The material was changed from stomach tissue to the silicone model to further the three-dimensional analysis. These results can be compared to those produced by the axisymmetric model to provide further confidence to the assumptions used. The concentric circular incision was tested first, followed by an analysis where the incision is a linear slit.
3.4.2.1 Concentric Circular Initial Incision

Building on the ideas uncovered from the three-dimensional analysis of gastric tissue, the silicone material model was substituted into the physical model. Similar to before, the Marlow model was initially attempted, yet it too was determined to be unstable for this analysis. The Neo Hooke model was found to be very stable for gastric tissue, so this was attempted for the silicone material. Duplicating the axisymmetric model tests, an initial ID of 10mm was deformed by another 10mm for a final ID of 20mm (Figure 3-41). It can be seen that this plot very closely mirrors Figure 3-34 the axisymmetric results of the same dimensions. Maximum strain in that model was 1.348e+05. This is only 3.78% difference between the two. Results from the other diameters also yielded similarly accurate results.

![Figure 3-41: Three-dimensional dilation of silicone model, ID=10mm, Deformation=10mm](image)

The accuracy of the silicone model in three-dimensions did more than just validate the axisymmetric model, it showed that the major difficulty in the 3D gastric model is directly related to the unstable material model. It therefore can be concluded that with a
more stable model from including different materials tests, the model will be more readily solvable. The silicone material is much more stable for a few reasons stemming from it only using an elastic portion of the stress-strain curve. The elastic stress-strain curve of the silicone material was nearly linear, making the use of said graph by ABAQUS much simpler than the bell-curve of the gastric tissue. For any given strain, there was only one stress value, and the opposite was also true. There was no ambiguity on the reported stress values. Secondly, because only an elastic material definition was used, the computational difficulty in transitioning to the plastic region is completely avoided. Both of these two characteristics, the silicone material proved to be much more stable which lead to an accurate and easier completing ABAQUS analysis.

3.4.2.2 Linear Initial Incision

In the operating room, it is far more likely for the surgeon to create an initial incision resembling a linear slit than it is for him to care a completely circular hole. The dilation of a linear incision poses new questions about the length, width, and the radii of the ends necessary for safe dilation. Furthermore, the concentric circle initial incision had very uniform stress levels across the model but due to the geometry there are areas of higher or lower stresses – and these needed to be understood.

The first attempt at the linear incision essentially eliminated all curvature from the ID. The slit was 2mm wide rounded at the top and only 10mm tall. Essentially, the slit is the same height as the final deformed diameter, but very thin, so it had to be dilated nearly the full width of the balloon. The simulation only proceeded to a time step of 0.6927 out of 0.8 to finish due to excessively distorted elements. See Figure 3-42 for the deformed contour plot.
The maximum stress was $1.016 \times 10^5$ Pa, which was quite similar to the stress level when a 10mm diameter incision expanded out to 20mm – $1.297 \times 10^5$ Pa. Even though the simulation did not run to completion, the closeness in stress levels showed that the stress did not rise significantly higher, despite the obvious stress concentration point. Furthermore, at the most-stressed area – the distal end of the incision – the levels of stress dropped extremely quickly along the radial direction. In fact, when the distal end is analyzed more closely, if this were human gastric tissue the stress levels drop quickly enough that only the previously damaged tissue would be plastically deformed, Figure 3-43. This shows that even a linear slit the same length as the desired final OD is capable of distorting large enough to allow the prototype passage while maintaining the integrity of the tissue.
Similar analyses were performed with slits ranging in height from 10mm-14mm, and altering the slit thickness from 1mm to 2mm. Remarkably, all results were nearly identical, the only difference being the distribution of the stress where the balloon makes contact with the tissue. It can be concluded that the worst-stressed area will be located at the top of the incision and despite this stress concentration, the levels decrease quick enough where excess tissue damage will be avoided.

Because the distal tip has a stress concentration, the most effective method of reducing stress is to increase the diameter. Keeping the slit the same dimension of 10mm high by 1mm wide, the distal tip was increased to a diameter of 4mm. As expected, the stress was decreased to only 55.8% of a slit without the enlarged tip. Furthermore, the stress was not nearly as concentrated to the distal tip and a second area of high stress is seen along the X-axis midline, but similar to the previous example it still decreased very quickly along radial lines. Figure 3-44 (A) shows the model before deformation, and (B) shows the resultant contour plot when deformed to accommodate the 20mm prototype.
Using finite element analysis proved to provide many benefits to device design, despite the numerous difficulties in defining and solving an accurate model. A significant amount of effort is used in ensuring the assumptions used to simplify the model do not adversely affect the final outcome. Of these assumptions, two were found to affect the results most: Z-axis symmetry, and the material model. In both the axisymmetric and three-dimensional models, the z-axis symmetry added additional stability to the model keeping the tissue from buckling. According to the axisymmetric full-thickness model, the buckling seen in the tissue was movement along the z-axis (into or out of the peritoneal cavity) rather than accordion-type multi-fold. Looking at beam buckling theory, this finding is understandable based on the fixed-free fixturing the situation displays. Despite the predisposition towards buckling, the Z-axis symmetry was used because the dual-balloons would act to stabilize the tissue and inhibit it from this motion.

By far the most important assumption was found to be the material model. Extensive effort was used in testing, analyzing, and translating the stress-strain properties into a useable property definition for ABAQUS. Even slight changes in the selected
hyperelastic strain-energy model created large differences in simulation output. The Marlow model was used exclusively for the axisymmetric model for both the tissue and silicone, yet was found to be unstable in three-dimensions. For the axisymmetric model, only a 2D cross section is defined, then ABAQUS rotates that in 360° for calculation – turning it into a full three-dimensional model for calculations. However, like the Z-axis symmetry plane disallowed buckling, there is enough of a stabilizing effect from axisymmetric which allowed a Marlow material to reach convergence. The Neo Hooke strain-energy model was found to be extremely stable and was used for the three dimensional analysis. This worked nicely for the silicone model, but the because of the complexity of the gastric tissue material, these results were far from expected and only the silicone tissue was used for further analyses. A circular ID similar to the axisymmetric model was accurately solved, then a linear incision with and without a stress-reducing distal enlargement. As expected, the stresses were concentrated at the distal ends of the slit, and highest when the radii was smaller.

Based on the FEA simulations completed, it seems as though a circular incision would be the most beneficial for reducing possible risk of inducing further tearing damage to the tissue. The dimension of said ID is approximately half of the final deformed diameter. However, in the likelihood that a straight incision should be used, creating a distal enlargement to the slit will reduce stress concentrations present in a small radius. The use of FEA has proven to be effective in determining the operating parameters in which this prototype will operate allowing for yet another level of confidence of safety to the patient.

4. Experimental Validation

Introduction

While various types of assumption verification can be made in the computer simulation through altering variables and analyzing the altered results, the true test of the numerical modeling comes in the form of experimental validation. However, many times it is nearly
impossible to test the exact operating parameters the simulation attempts to duplicate. To get around this, a more simplified test case is used. In this instance, the largest questionable variable lies in the properties of the gastric tissue. To fully trust this model, the same procedure using substances of known material properties was also analyzed in the hopes that this material is easier to obtain and more uniform.

4.1 Experimental setup

It is the ultimate goal of the experimental setup to exactly duplicate all of the assumptions and verified simplifications used in the computer simulation. Some of the most important assumptions are the IC’s and BC’s as these are physical assumptions that must be accounted for during design of the experiment. Recapping the BC’s, they are: X- and Y-symmetry planes separating the model into quadrants, and encastre conditions of the OD isolating the model. The first BC’s of symmetry planes are assumptions that are used during computerized FEA simulations to reduce computational expense. It would also be difficult to mimic the IC of ID pressure or displacement with only a quarter-symmetry physical model. Additionally, in an effort to keep the experimental setup generalized, the full model was used.

The other BC to fully encastre the OD is much simpler to duplicate, however. Referring to Figure 4-1, the experimental model was created with two parallel acrylic plates to clamp the tissue between. Both plates have concentric holes mimicking the OD of the computer simulation. To ensure the tissue is adequately fixed at the edge of said holes, the pink plate has an acrylic tube which places all the clamping pressure on the thin edge not allowing the tissue to slide. In order to place the tissue in this test fixture taught but without stretch or sag, spring-loaded hinges were included to aid in fixturing the tissue properly before clamping. The holes in each plate are kept concentric with alignment pegs ensuring the proper clamping location of the acrylic tube. The parallel plates are kept vertical with aluminum angle, which is fixed to each plate. One is rigidly fixed to the base allowing for a free standing experimental platform. Finally, a fixturing jig to hold the dilation balloon and camera centered to the concentric holes for experimentation and measurements are included. Prints are located in Appendix C.
In order to perform experiments in this setup, a piece of tissue or tissue substitute is placed over the hole on the stationary plate. It is then adjusted for proper tension and held in place by the spring-loaded hinges. Next, the second plate is slid into position clamping the tissue in place. A dilation balloon is slid into the initial incision and placed in its fixturing jig to isolate only balloon expansion and not bulk movement as the dilation force. Finally, the camera is attached to the opposite side and digital pictures taken at regular intervals during expansion. The balloon was inflated to several different maximum sizes to observe the difference between expansion characteristics of the tissue. These experiments correlate to the simulations performed in ABAQUS.

4.2 Recording and Data Processing

In order to validate the computer FEA simulations the experimental results must be digitized and compared. The digitization was performed through using digital still pictures from the camera in Figure 4-1. Images were taken pre- and post-expansion for the final strain determination. Processing this data was completed through the use of a MATLAB user defined program. Data points from the digital images were read into the program and the strain calculated based on the change in position of nodes drawn on the test sample. From the strain, stress was looked up in a material properties table and graphed in a similar style to the ABAQUS plots. With the data recording and processing
routines the experimental data can be compared to the ABAQUS simulations for verification and validation of the assumptions used.

### 4.2.1 Digital Recording

Upon initiation of the experiment, the first step in accurately recording the deformation of the simulated tissue polymer was to draw a grid in a radial coordinate system. An initial digital picture is taken and the intersection of each radial and circumferential line is measured and recorded. The picture is loaded into xyExtract.exe V4.1 (2008) written by Wilton P. Silva. This program is able to accurately measure the coordinates of any points after an x- and y-axis is established. For the sake of simplification, the origin of the quarter-symmetry model is taken to be the center of the plot. For the half-symmetry models the origin is the left-most point on the horizontal symmetry plane. All images were taken from an Olympus Stylus 770 SW 7.1 megapixel digital camera using the super-macro digital zoom feature. The camera was stabilized on a threaded rod fixed to the base of the experimental setup. To isolate any vibrations from depressing the shutter-release button, each image used a five second timed delay after the shutter button was depressed.

### 4.2.2 Data Processing

Post-processing of the images taken from the digital camera was completed through a user-defined MATA LB program. This program works very similar to a commercial finite element analysis program in 2D, but specialized for this special case usage. The Cartesian coordinates of the intersection points from the cylindrical coordinates are recorded using xyExtract.exe for each of the regular intervals previously established. Each image must maintain the same node order, so the nodes were ordered on radial spokes originating from the origin. Taking into account the difference in the initial and final node positions, the program then is able to calculate the strains. Knowing the strain value of each element, the stress is then looked up from the material properties table established from tensile testing, and finally the deformed shape is plotted with a color map corresponding to the relative intensity of stresses in each element. The deformed color map is plotted on
top of a line drawing of the original shape to show the extent of deformation. See Figure 4-2 for a sample of this style of plot and associated grayscale color map.

This method of optical analysis should be regarded as an estimation process to validate the relative accuracy of the computer FEA simulation. It should be considered an estimate because there is no volumetric data associated with the two-dimensional calculations. In this regard, the thickness is essentially ignored. Considering the physical model is a thin section of tissue rather than an infinitely long cross-section the assumption of no thickness introduces some degree of error. However, the ABAQUS FEA simulations showed that the stress levels at the center plane of the tissue were quite similar to a plane taken at near the exterior edge. The experimental calculations neglected thickness by assuming the tissue midline was used as a representatively plane to calculate stresses. The following section will look at the differences and similarities between the experimental and computer FEA models for a silicone sheet in an effort to verify the FEA techniques for balloon expansion of thin tissue sections.
4.3 Overview

The experimental setup used to validate the FEA model is quite simplified when compared to the actual surgical environment of the device. The FEA model needed to be simplified in order to accurately focus on the area of concern and reduce computational effort in areas of minimal importance. The experimental model was able to effectively take these simplifications and apply them in a physical experiment. Before and after images of the dilatory process were taken, digitized through xyExtract, and finally strain and stress values calculated based on the deformation in a user-defined program written in MATLAB. This experimental setup is robust enough to be used in nearly any incision and loading mechanism possible for this type of surgical intervention.

5. Experimental Process

Due to the complex nature of the stress-strain plot of human tissue, finding another material to exactly replicate the properties for experimentation was unlikely. Instead, a set of experiments were carried out with a 10A durometer silicone tissue substitute. The same experiments were performed as the FEA simulations, and the results compared to the computer model to show the validity of the assumptions.

5.1 Balloon Expansion

The original plan was to perform the majority of experiments with dilation balloons. Balloons of known maximal diameter would be expanded with a pressure-monitored syringe to deform the polymer tissue substitute. While it would have been ideal to have several different non-compliant balloons of known maximal diameters, this proved cost prohibitive for this project. Instead, Fast Forward Medical in Plymouth, MN donated two raw prototype balloons. Though developed for a different procedure, this shows the general style of balloon – two areas of larger diameter separated by a small valley. The valley eliminates the risk of the tissue falling off the front or back end during expansion. Figure 5-1 (A) shows the un-inflated balloon while Figure 5-1 (B) shows the inflated form. This balloon is unfortunately unusable for this application because of the
requirement to be mounted on a hard inner lumen which would not fit through the working channel of an endoscope, nor allow an endoscope to pass through once deployed.

Figure 5-1: Lumen-mounted dual-donut balloon supplied by Fast Forward Medical

Though the expansion proceeded quite nicely, several problems were encountered which led to abandoning balloon dilation for experimental validation. First, both the silicone tissue substitute and the balloon were compliant materials, and achieving a stable diameter proved quite difficult. Despite the valley controlling the axial movement of the tissue, the bulbous regions expanded much larger than expected due to the center constriction. This led to the second problem, accurately measuring and digitally capturing the tissue movement. Merely measuring the diameter without distorting the balloon was nearly impossible. Furthermore, because the camera was positioned essentially in a Z-axis offset to the tissue plane, the bulbous OD of the balloons blocked visualization of the tissue very near the ID – the area of most interest and importance, (Figure 5-2). One very interesting observation that was made with this balloon was its ability to center itself on the silicone. Furthermore, the balloon stayed positioned even when twisted, axially
displaced, and twisted in many directions. This gives support that the dual-donut balloon distal end will both create an adequate seal between the stomach and peritoneal cavity while staying in place during endoscope manipulation during the intervention.

![Figure 5-2: End-view of balloon dilation of silicone](image)

5.2 Rigid Object Dilation

Pushing rigid objects through the small incision in the silicone is very far from the reality of the actual surgical operation. Even still, the MATLAB FEA program only takes the initial and final position of the nodes, so using a rigid object to dilate the hole is essentially inconsequential to the actual analysis that will take place. Since rigid objects are far easier to obtain in a variety of sizes than surgical balloons, almost any diameter is possible. In order to experimentally validate the model, diameters were chosen which matched those used for the ABAQUS simulations. Furthermore, seeing as the rigid object can be much longer than the thickness of the silicone, the material will not slip off eliminating the necessity of the valley the balloon needed. This also means the deformed nodes will be easily visualized – a major problem from balloon dilation.
The final deformed diameters for the experiments were the same used for the FEA simulations. However, these displacements for ABAQUS were chosen specifically based on the ability to readily source items of known metric diameters. With an initial diameter of 10mm, final deformed diameters of 12mm, 14mm, 16mm, 18mm, and 20mm were selected. Items were found at the local hardware store which were closely matched these dimensions. Each rigid object was unfortunately slightly undersized, but this was remedied by applying several wraps of clear tape to build the thickness. Figure 5-3 shows each item used for the rigid dilation.

Putting each of these into the incision was not as elegant as simply inflating the balloon because the front of the rigid objects is blunt. The blunt edge created problems inserting it without damaging the material or smudging the dots drawn on it. To reduce these risks, a small cone was constructed from tag-board to act as an introducer. Once inserted, the silicone deformed exactly the same as the balloon, but with much better visualization of the nodes directly near the ID. Figure 5-4 shows the silicone in the experimental apparatus with the 14mm object inserted. Notice when the radial displacement is relatively low, the material plane remained relatively flat. The white strips on the top and
right of the circle contain a millimeter scale which is visible when zoomed in for dimensional analysis.

![Silicone mounted in test apparatus with 14mm object](image)

**Figure 5-4: Silicone mounted in test apparatus with 14mm object**

The largest problem encountered when radially dilating the silicone material was with the material buckling and moving out-of-plane. Typically, the material moved in one direction (into or out of the page) as a free-fixed buckling mode rather than a fixed-fixed accordion-type buckle. The ABAQUS simulations used a mid-thickness symmetry plane which stabilized the model from buckling. To simulate this stability, the rigid objects were held to keep the tissue substitute from moving axially. Even still, because the material was held as fixed-fixed at the ID and OD rather than fully constrained at mid-plane, it showed signs of bucking with higher amounts of deformation (Figure 5-5).
In the previous two images, faintly visible on the silicone are the nodal positions. These were used to compare pre- and post-deformation images. The first step in defining the nodal positions was to establish an accurate coordinate system. The scaling system on the top and right side of the silicone was placed where the tangent lines were horizontal and vertical. This allowed a precise digital measurement of the diameter. Two intersecting full diameters located the center. While it seemed most logical to define the origin at the center, problems may arise with the MATLAB program if any of the nodal points cross over into negative values. Therefore, a position two millimeters to the left, and two millimeters down (measurements formed from the scaling system) was used to keep all points positive at all times.

After the origin and coordinate system was defined, the nodes needed to be digitized using xyExtract. The program is fairly basic and does not allow for zooming or repositioning of nodes after a specific position is selected. Furthermore, the language of the MATLAB program necessitates the order of nodal input be in the same order for each test. Because of these difficulties with the program, it seemed pertinent to precisely locate all of the nodes prior to importing the image into the program. This also ensured an accurate count of each radial spoke and concentric circle so the post-processing would proceed without errors. An example of the nodes for the 14mm dilation is seen in Figure 5-6.
This process was completed six times: once for the pre-deformed shape, and once for each of the deformed shapes. As the degree of deformation increased, it became increasingly difficult to locate the nodes closest to the ID because of material buckling. Once all the points were located, they were digitized with xyExtract. In this program, the origin and maximum on the X- and Y-axis are selected and defined thereby eliminating any errors from a difference in image size. After the axes were defined, each point was individually selected along radial spokes starting at $\pi/2$ radians and moving clockwise. The output from xyExtract was a text file of two columns of the X and Y position of each node, with each node represented by a single row. In this manner, the node numbers aligned perfectly from one test to the next ensuring the MATLAB output was correct.

### 5.3 MATLAB FEA Output

With all of the nodal positions digitized for the pre-expansion and post-expansion experiments, the text files were read into the user-defined MATLAB program. The distance between adjacent nodes was measured for the initial and final positions, and the
strain calculated. The material properties of the silicone tissue substitute have been determined through tensile testing, so the stress value for each element was determined by matching the strain value from the stress-strain plot. Darker colors represent higher stress while lighter colors represent lower stress. Figure 5-7 shows the stress contour plot when the ID of 10mm was expanded to the maximum size of 20mm (results of other expanded sizes are in Appendix B). The small “+” and dotted lines represent initial nodal and element positions, while the diamond-shape and grayscale lines indicate final nodal positions and elemental stress values.

This experimental result was compared to the ABAQUS output to validate the FEA model. Three metrics were of particular importance: displacement, maximum stress, and “style” of deformation. Comparing the displacement of the experimental model was quite simple. The FEA model prescribed an initial ID expanded out to a very definitive final ID of 20mm. In the experimental model, a punch of 10mm was used to create the initial incision, and a rigid object sized at 20mm was pushed through to expand the incision. This also should result in a very definitive final silicone ID of 20mm. Looking back at
Figure 5-7, the initial ID is seen underneath the contour plot. The nodal positions of the ID do not line up exactly with 5mm on the X- and Y-axes as would be expected from an initial ID of 10mm. However, remember there was a 2mm offset to the axes, so they are only useful in determining positions relative from before and after deformation, not absolute coordinates. So, if the undeformed ID is assumed to be exactly 5mm, and it is known that each node is spaced radially 1mm from the next, the change in deformation can be counted easily. Along the X-axis, the contour plot has been deformed almost exactly 5mm. However, as one travels counterclockwise towards the Y-axis, the deformation seems to increase to nearly 6mm. While this may indicate slight errors, this experimental model showed significant problems of instability and buckling, so the ID may have deformed in a non-uniform manner. If the bottom had not buckled as much as the top, this could skew the rigid object vertically producing the seemingly larger diameter. It is also possible the rigid object was not held in exactly concentric to the undeformed ID. While steps were taken to keep the axis of the rigid object collinear with the central axis of the incision, unequal forces on all sides from buckling could have slightly offset the deformation. Even with the slight error, the deformed plot still shows a very close approximation of the dimensions used in the simulation completed in ABAQUS.

The next metric compared was maximum stress. This was fairly important because all of the design decisions for the balloon sizing and incision sizes were based on the maximum stress the tissue could safely handle. From the ABAQUS simulation, the maximum stress from a 10mm ID expanded to 20mm for the silicone was found to be 1.348e+05 Pa. Again referencing Figure 5-7, the maximum stress from the experiment was determined to be 1.292e+05 Pa, which is only a 4.2% error under expected. See Table 5-1 for the results of the other tests.
Table 5-1: Comparison between MATLAB and ABAQUS FEA output

<table>
<thead>
<tr>
<th>Final ID (mm)</th>
<th>MATLAB Output (Pa)</th>
<th>ABAQUS Output (Pa)</th>
<th>% Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td>63,189</td>
<td>25,050</td>
<td>143.50</td>
</tr>
<tr>
<td>14</td>
<td>67,080</td>
<td>51,010</td>
<td>31.50</td>
</tr>
<tr>
<td>16</td>
<td>102,298</td>
<td>77,230</td>
<td>32.46</td>
</tr>
<tr>
<td>18</td>
<td>113,000</td>
<td>105,000</td>
<td>7.62</td>
</tr>
<tr>
<td>20</td>
<td>129,160</td>
<td>134,800</td>
<td>-4.18</td>
</tr>
</tbody>
</table>

It can be seen that the percent error is very small for the last two tests, 18mm and 20mm. However, as the deformation decreases the error increases dramatically. The exact reason behind the drastic increase in error is not known, but one theory prevails. When the initial incision was cut from the silicone, a punch was used. While effective in cutting a perfectly circular hole, the punch created a hole with varying diameters through the thickness, (Figure 5-8). This happens because the nearly incompressible soft material begins to compress and is displaced radially under the punch before shearing begins (B). Then, after the punch has cut through the silicone and is removed, the material springs back to its original undeformed shape (C). This would affect the low deformation tests more because the excess material on the ID is a larger percent of the diameter than in higher deformation tests.

![Figure 5-8: Deformation of silicone while being punched](image)

During the digitization process, each point had to be first accurately located, then a small dot overlaid on the image to make the exact position more clear, then accurately located again when selecting points in xyExtract. Each time the data point was located a small amount of error was introduced in the system. The question that arose was: how much error was produced? While it is difficult to exactly say for the first two steps, the last step produced quantitative numbers which could be compared quite easily. To do this a simple
test was run using a single element. The test element was first very precisely measured in xyExtract on the predeformed plot. On the 20mm final ID plot, a measurement was taken to establish a baseline for the strain. Testing the sensitivity of the strain to the resolution of the program, one node was moved by one pixel, slightly elongating the element thereby increasing stress.

Table 5-2 shows this sensitivity study. Points 1 and 2 were located in the predeformed model. These points were specifically chosen because they were very near the ID and nearly perfectly horizontal from each other. This later fact isolates the effect from the width of one pixel. The nodal positions were again taken in the 20mm deformed plot for the same two points. Finally, in this deformed plot, Point 2 was moved one pixel to the right elongating the deformed element very slightly. The distance between deformed nodes was increased from 1.113mm to 1.176mm from the one pixel alteration which increased the strain from 0.4471 to 0.5016. Looking up these values in the silicone material properties table showed an increase in stress from 38,825.9 Pa to 42,556.4 Pa. It can be seen in Table 5-2 that moving Point 2 by only one pixel created an absolute position change by 0.04mm which resulted in 9.61% error in the stress of the element. This would have a cascading effect through the rest of the model because the next element over would be slightly shortened. This error would likely rise as the undeformed element became smaller. Moving one node of the element by one pixel would have a larger percent change of the element. If an element was only 4 pixels wide, one pixel increase would result in a 25% change in length. Also, by the time strain was calculated, each node had been manually selected three times. While it seems unlikely for the node to translate three times in the same direction – especially since the first two times it was selected a zoom feature was used to increase positional accuracy – this shows a non-negligible amount of error can be attributed to the process of locating the position of the nodes. Clearly, the experimental analysis is incredibly sensitive to precise positioning of the nodes during each step, may account for the majority of the error in reported stress levels.
The last metric to be compared was the style of deformation. This qualitative analysis is used as a “gut check” to make sure the analysis completed uniformly and the areas of high and low stress were found in their expected locations. Once again the 20mm final ID tests were used for comparison. Figure 5-9 shows both the quarter-symmetry experimental/MATLAB result (A) and the axisymmetric ABAQUS model (B) directly next to each other for ease of comparison.

### Table 5-2: Results from sensitivity study of xyExtract on stress in elements

<table>
<thead>
<tr>
<th>Deformed Element</th>
<th>X (mm)</th>
<th>Y (mm)</th>
<th>Distance (mm)</th>
<th>strain</th>
<th>Stress (Pa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Point 1</td>
<td>1.73</td>
<td>12.01</td>
<td>1.133</td>
<td>0.4471</td>
<td>38825.9</td>
</tr>
<tr>
<td>Point 2</td>
<td>2.86</td>
<td>12.14</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Stretched element by One Pixel</th>
<th>X (mm)</th>
<th>Y (mm)</th>
<th>Distance (mm)</th>
<th>strain</th>
<th>Stress (Pa)</th>
<th>% Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Point 1</td>
<td>1.73</td>
<td>12.01</td>
<td>1.176</td>
<td>0.5016</td>
<td>42556.4</td>
<td>9.61</td>
</tr>
<tr>
<td>Point 2</td>
<td>2.90</td>
<td>12.14</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
To provide some orientation, Figure 5-9 (A) shows the quarter-symmetry model, essentially viewing the flat plane of silicone. Figure 5-9 (B) shows the ABAQUS model where the silicone material is rotated into the page 90 degrees, so the contours are on the thickness of the silicone. The most important feature of both graphs is they both show the highest stress in elements directly adjacent to the ID with levels dropping off dramatically along the radius. Additionally, the majority off the radial dimension has relatively low stress levels. These two features show the “style” of deformation for the physical experiment output through MATLAB very closely resembles the output from ABAQUS.

The last benefit the MATLAB calculations are able to provide is in understanding the relative distribution of stress in the radial and cylindrical directions. Figure 5-10 shows a
close-up view of the worst stressed area of the 20mm rigid object deformed silicone – the ID. The final nodal position markers were removed because many of the radial elements are very small making visualization difficult. Comparing the relative stresses in the radial and circumferential directions, by looking at the grayscale value of the lines it is clear that the circumferential direction is stressed higher than radially.

Extrapolating this idea to the actual surgical intervention with human gastric tissue, if the material should fail during balloon expansion, it would be due to circumferential tension rather than radial compression. Logically, this makes sense also since in the radial compressive direction the tissue would likely fold and buckle. The material is too soft and pliable and does not have the stabilization necessary to reach compressive failure. Taking this idea one step further, the highest tensile load is seen very close to the ID. In fact, measuring from the graph (the predeformed nodes are approximately 1mm apart), the highest stresses dissipate within 1mm of the ID. This dimension also correlates to the damage caused by the electrosurgical incision through the tissue, so only the already corrupted material will undergo excessive tensile loading leaving the rest of the tissue intact. Suturing or other tissue-approximation efforts would shy away from this region very close to the ID to reduce “pulling-through”, and since risk for tears is limited here, the surgeon can be confident in suture placement and a tight seal without worrying about perpendicular tears in difficult locations.
5.4 Overview

This style of dilation where the balloon is infinitely long in relation to the thickness of tissue, and where the direction of expansion is parallel to the thin tissue plane has not been described in the literature. After the FEA analysis was complete, an experimental simulation was performed to ensure the assumptions used yielded an accurate solution. A grid of nodes was transferred onto the silicone and measurements taken before and after deformation. After digitized and analyzed in MATLAB, the results were compared to the output from ABAQUS. The displacement seen from the experimental results were very close to the expected final diameter. Issues such as buckling and alignment of the rigid object may have accounted for the slight discrepancies. Under high amounts of deformation, the results from both simulations showed nearly matching results. Low deformations had large amounts of error, possibly attributed to the use of a punch to create the initial incision. Compounding the error, a large amount of error was introduced in the process of digitizing the nodes – 9.61% error was found from a node moved one pixel. Even still, all graphs when compared from MATLAB to ABAQUS showed similar styles of plots with high and low stresses seen in expected places. Despite some of the
errors between the MATLAB and ABAQUS outputs with low deformation, the large deformation plots shows the assumptions used in the ABAQUS model are accurate for the silicone material. In the computer simulations, the only difference between the analyses of human gastric tissue and the silicone tissue substitute is the material model. This experimentation has shown the simulations using silicone tissue are accurate; therefore extrapolating from these findings lead to the conclusion that the analyses performed of the human gastric tissue undergoing balloon dilation are also accurate. This adds an additional degree of confidence in the proposed lumenally delivered, flexible, balloon-assisted, sterile endoscopic overtube.

6. Device Prototypes

As much of an art as a science, designing balloon prototypes presents a unique difficulty due to the large difference between the dual operating parameters which it must operate under. First, the balloon needed to be compressed to fit through the working channel of the endoscope. Next, this inflated balloon performs under unique operating conditions which have only now been fully realized. Additionally, the style of balloon is a recent development and many uncertainties arose with a balloon without a rigid inner lumen. To further complicate the design process, physical prototypes were unable to be constructed. Even still, several possible methods of prototype construction are reviewed for future development.

6.1 Prototype Design #1

The first possible method of prototype construction is also the most simple. The general idea of the entire project was for two donut-shaped balloons on a flexible sheath. This thought was progressed into a very simple idea – donut-shaped balloons (yellow) glued to the distal end of a thin flexible sheath (green), Figure 6-2. In order to fill the balloons, small filing tubes (red) would need to be attached to the balloons and trailed proximally parallel and exterior to the sheath. Prior to use, it would be wrapped around a thin lumen for an electrosurgical implement and finished by wrapping in a thin zipper-sheath for ease of loading into the endoscope. In a related project, several donut-style balloons were
manufactured by FP Solutions Group, Exeter, NH. Shown both deflated and inflated in Figure 6-1, a similar design could be used for this prototype. The two prototypes represent two different materials and thicknesses which could be used.

![Figure 6-1: Donut balloons created by FP Solutions Group: deflated (left), inflated (right)](image)

Two different methods of filling are shown. In Figure 6-2 (A), a single filling port would be used; with both balloons being filled simultaneously. This has the advantage of simplifying the device and reducing the material – essential for decreasing the compressed size of the device to fit through the working channel. Figure 6-2 (B) shows an embodiment where two filling tubes would be used; each balloon being filled independently. While there is an obvious disadvantage of more material, a major advantage of this construction is the ability to inflate the balloons independently. In this manner, the distal balloon would be inflated first and slightly pulled back while the proximal balloon is inflated to ensure the tissue stays in-between the balloons and does not slip proximal or distal to the set of dual balloons.
Even though this seems like a very simple design, it would actually be difficult to manufacture since the device would rely quite heavily on the glue joint between the balloons and the sheath. This glue joint becomes problematic because the sheath must be a lubricious material – such as PTFE which has one of the lowest coefficients of friction between 0.05-0.09\textsuperscript{234} – and the very properties of low surface energy and chemical inertness which creates the non-stick surface also inhibits many types of glue from being effective.\textsuperscript{235} The material must first undergo a surface preparation like electrochemical reduction, sodium solution etching, or glow discharge modification on order for bonding to be effective.\textsuperscript{236} Because of this, the manufacture becomes more complex for a seemingly simple device. Finally, the ability for the two balloons to pull the tissue out rather than pushed out is uncertain. After conversations with balloon manufacturer Fast Forward Medical, two more prototypes were brought to light.

### 6.2 Prototype Design #2

The second prototype design builds off of the general idea of the first, but instead of two separate balloons, a singular balloon is used. The single balloon is configured more in a corkscrew manner with a small section of a noncompliant “girdle” and reducing crimps midway between to form the dual donuts, Figure 6-3. This section of crimps in the balloon has an additional advantage as only one filling tube is necessary. As the balloon expands it will force the noncompliant section to the designed OD – pulling the sheath out with it – thereby reducing the reliance on glue or other adhesives between the
balloons and sheath to expand the incision. This will allow the balloon and sheath to be made from different materials allowing optimum material selection to match the operating parameters for each portion. Adhesive would still be used, but less importance and stress would be placed on said joint.

![Figure 6-3: Prototype Design #2](image)

The manufacture of this prototype would unfortunately still require processing of the PTFE sheath to attach the balloons. However, this process could be simplified by constructing the balloon section as a separate subassembly lessening the precision needed for fixturing onto the sheath. Construction of the balloon section (dotted lines) would begin with a short section of urethane tubing the same diameter of the sheath. Next, a section of urethane tubing of the desired balloon dimensions would be sealed on proximal and distal ends, a filling port added, and reduction crimps made in the middle, (Figure 6-4). These reduction crimps would not allow this section from expanding when the balloon are inflated – essentially turning this portion into connecting tubes. It would be wrapped around the urethane sheath and the middle section wrapped with a noncompliant material to properly position the two sections of the uni-balloon. The final step is for this
section to be attached to the preprocessed PTFE sheath and tubing attached to the balloon filing port. This too would utilize a central needle knife lumen and zipper-sheath.

![Figure 6.4](image)

**Figure 6-4: Expanded view of the one piece donut balloon**

The major benefit of this prototype over the first one is the reduction in stress placed on the adhesive joint between the sheath and balloon. The balloons and crimped section are all one piece, so as the balloons inflate the section between them is also forced to the same diameter. This coupled with the noncompliant girdle around this section forces the ID of this subassembly to a known diameter. Even still, this assembly is far from simple to assemble. The final prototype aimed to combine the simplicity of the first design, with the deviation from relying on the glue joint of the second.

### 6.3 Prototype Design #3

The last prototype design combines the best features of both of the previous designs. The balloons in the first design are quite simple, without the complex corkscrew shape with a center crimped section. Partly due to the section of non-compliant material in the second design, the reliance on the adhesion between the balloons and the sheath is reduced. Figure 6-5 and Figure 6-6 show the prototype before and after the balloons are inflated. The two balloons are attached to the inner sheath with an adhesive. As they are expanded, they will pull the sheath out to the final desired diameter. This action will not, however, be fully responsible for the dilation of the tissue. The outer sheath is made from a compliant material that deforms with the balloons as they are filled. This tension in the outer sheath is what forces the tissue to the desired diameter to allow the endoscope into
the peritoneal cavity. The outer sheath between the two balloons could be modified with excess material or altering levels of compliancy to allow the valley to conform to desired dimensions.

Figure 6-5: Prototype #3 before balloon expansion

Figure 6-6: Prototype #3 after balloon dilation

Similar to the other two prototypes, this one also centered around the PTFE inner sheath and dual-urethane balloons with a single filling port. The manufacture, therefore is nearly as simple as the first design. The only alteration, essentially, is the outer sheath which would provide a superior method for dilating the stomach tissue. Even though the valley
of the outer sheath is nearly the same diameter as the inner sheath, it is placed in tension by the dilation of the balloons and is therefore able to pull the tissue out as though it was being dilated by the balloons themselves. This outer sheath would be made as a separate subassembly and joined to the inner sheath both the proximal and distal end. An added benefit of the dual-sheath design is the space between along the length of the device can also be inflated. The overall OD would change little because there is very little space between, and inflation pressure would be low, but this long cylindrical balloon will give the sheaths extra rigidity. Added rigidity will reduce the risk of binding and more closely simulate semi-rigid lumen (the space where endoscopes were designed to be used), giving the physician additional support to the surgical instrument.

6.4 Overview

Each of the three proposed prototypes has their own benefits and drawbacks. The first has a very simple design, but relies heavily on the joint between the balloons and the sheath. The second reduces this risk with the corkscrew-style balloon, but this subassembly manufacture increases both cost and difficulty. While also simple, the third adds the outer sheath which decreases reliance on the adhesive joint between the balloons and the inner sheath, but adds more material to a device already pushing the envelope to fit through the working channel of an endoscope. If they do not fit through the working channel, additional improvements – or even a new introducer endoscopic platform – will be incrementally made until the size metrics are met. Overall, the only true way to determine if any of them work is to produce working prototypes and test them in the lab, then animal subsequent studies. Final surgical use seems a long-way off from these paper prototypes, but with the background research showing how they will work in the body, the effects of the device on the tissue is now known which will decrease the project lifecycle reducing the time needed to bring this device to be brought to market.

7. Conclusion

This final chapter provides a closure to the work in three distinct sections. The first will aim to provide a review of the major focus of each chapter. Next, conclusions of this
work are drawn with focus given to areas of significant contributions to the literature. The last section aims to provide insight into further work to advance the understanding of balloon dilation of the gastric tissue.

### 7.1 Review

The overall goal to this research topic was to create a lumenally delivered, balloon-assisted flexible endoscopic overtube primarily for use in the emerging Natural Orifice Translumenal Endoscopic Surgery (NOTES) style procedures. The work to create the prototype was multi-faceted, with four major areas of research contributing to the body of this work: background literature and patent review to understand the current state of knowledge and development of devices in this field; testing and statistical analysis of the human gastric tissue, FEA experimentation in ABAQUS, and MATLAB validation through physical experimental. Each area contributed to the literature and provided necessary insight for prototype development.

The first chapter begins by providing historical background on the advent of the modern NOTES procedures and its acceptance in medicine before the newly coined term. It also gives understanding to the motivation for pursuing such extreme methods of minimally invasive surgery through looking at early studies and extrapolating results when compared to laparoscopic interventions. A broad overview of each of the three major and one minor access points (gastric, colonic, vaginal, and vesical respectively) and its role in the field is given to appreciate the need for prototype development. Finally, a patent search is described showing a clear gap in IP for the prototype endoscopic sheath, showing potential viability for the results of this research.

The following chapter discusses the material properties needed for subsequent ABAQUS simulations and experimental validation. The bulk of work is dedicated to human gastric tissue, as it is currently sparsely reported, and widely varying in the literature. Tensile testing and statistical analysis were completed on both the inner and outer layers, and zero and ninety degree orientations of the tissue. The silicone tissue was assumed to be
uniformly homogenous and isotropic, so only a limited number of tests were conducted and no statistical analysis was necessary.

Chapter three starts with a brief background on FEA, and the assumptions which were used in order to create the various models. Decisions such as the mesh and BC’s/IC’s are explained, and most importantly a discussion on the material model for both gastric tissue and the silicone material to most accurately represent the material is given. Next, modeling the surgical simulation in axisymmetric and three-dimensions were compared and contrasted. Finally, conclusions based on these simulations are presented as a recommendation for surgical incision through the gastric tissue.

The next two chapters discuss the experimental process used to validate the FEA results. Chapter four specifically focuses on the setup and methods used to most accurately duplicate the computer simulation. A fixturing apparatus was designed and built to hold the silicone material for balloon dilation. A method for creating and digitizing nodal coordinates to measure strains in the tissue is also presented. Chapter five expands on the setup to show the results from expansion of the incision. It was found that balloons – while the optimum method for radial dilation – are not conducive for this experiment because their deformation distorts visualization of the nodes. Results from these experiments showed very close correlation to the finite element model, thereby validating results from chapter three.

The culmination of this work is shown in chapter six which showcases three prototypes designed to successfully pass through the gastric barrier into the peritoneal cavity safely and effectively. The first design is very simplistic, but relies heavily on a bond between the balloons and the PTFE sheath to dilate the tissue. The second prototype decreases the importance of said bond, but with the cost of an increasingly intricate balloon. The final uses the simplistic nature of the first design, but adds an additional external sheath to assist in dilation and provide sheath rigidity during the procedure.
7.2 Conclusions

One of the most surprising aspects of the literature review was the finding that the field of natural orifice surgery is not, as some like to believe, a new area of surgery. In fact, it can be contested that if one were to adhere to the literal definition of NOTES (natural orifice, translumenal, endoscopic surgery) the origins actually date back well over 100 years ago to the first culdoscopy by Dr. Von Ott. In 1901 he was the first to report using a natural orifice to perform surgery on organs externally adjacent to the introductory lumen. Throughout the next eighty years, natural orifice surgery remained limited to the pelvic region, however these types of interventions become accepted and more commonplace and within medicine. The next major advancement came in 1980 with the PEG tube. This radically new procedure allowed placement of a feeding tube directly into the stomach without the need for open surgery. It is the author’s belief that the success in the acceptance to safely perforate the stomach paved the way for modern NOTES interventions.

Modern NOTES is defined as the advent of using any of the major or minor access organs to perform surgery on organs that are not directly adjacent to the access organ; for example, transgastric hernia repairs. In these procedures, the surgeon must perforate the access organ, and cross the peritoneal cavity. This requires a new set of skills, techniques, and tools to operate safely and most effectively. To date, relatively few new devices are available to the surgeon, and when a survey of both previously accepted and new tools was taken, few of these directly focus on sterility. The current attitude towards sterility is lavaging and prophylactic antibiotics to decrease risk. However, the same papers that tout such cavalier attitude towards sterility have also had peritonitis and sepsis occur in animal trials. Some of these problems were encountered from the incision inadvertently expanding due to endoscope manipulation. The focus of this research was then aimed to tackle the as yet unrecognized need for a device to both provide sterility, and at the same time protect the incision site and organs such as the larynx from damage during the intervention.
Rarely reported in the literature, the material properties of gastric tissue are widely varying. The maximum stress and strain levels were so widely varying it was highly questionable as to which ones were accurate. It is believed that the pull-rate during tensile testing were to blame for inaccuracies in the reported data. Tissue is considered to be viscoelastic, and as such the material properties are a function of the pull rate. The load rates used in reported data were two orders of magnitude higher than what was used in this research. The purpose for the much slower load rate is that it more closely represents the loading mechanisms used during surgery, so FEA results using these properties will more accurately depict the actual results. Furthermore, while the 0° and 90° orientation of the stomach visually show different muscular directions, they were found to be statically insignificantly different for much of the stress-strain curve. Tissue is known to be slightly different from one person to the next. The variations from one patient to the next, and natural variations within each tissue sample reduced the possibility to statistically show differences. This work was also the first to report the full stress-strain curve for the different layers of the human gastric stomach. Again, found to be mostly statistically indifferent, this greatly expands the understanding of the strength of the stomach organ. It then becomes clear that while it is advisable to repair both layers of the stomach in order to fully recover the strength of the native stomach, as long as either layer is fully repaired the mechanical strength will be adequate.

There were very few tensile tests completed for the silicone material, and a certain degree of data manipulation to obtain the full stress-strain curve. This was done because it was assumed that if a tensile test were performed perfectly each time, there would not be any deviance in the data due to material homogeneity. Operator error accounted for nearly all the error in the stress-strain curve. Curves were averaged and extrapolated to produce the most accurate plot as possible. Additionally, it was inconsequential that the tests samples were not stressed to failure, since neither the FEA nor experimental model saw strain values high enough to encounter complete failure of this material.

FEA analysis is only as accurate as the assumptions prescribed by the user in the simulation. During different trials, the mesh was altered slightly, IC’s and BC’s changed,
and different simplifications used. Each modification, aside from buckling when the Z-axis symmetry plane was removed, had very little impact on the final result. The most important assumption was in how the material model was input into the model. Elastic and plastic region definitions greatly affected the final result. Unfortunately, during analysis it was discovered that during the three-dimensional modeling the gastric model proved to be unstable from lack of data from different methods of testing (biaxial, volumetric, etc). Had this data been available it is likely that convergence would have been easier to reach.

It was found that when a purely circular initial incision is used, the axisymmetric model identically duplicates the results from a much more complex three-dimensional model. While this may be important, the far more likely scenario of a linear incision can only be represented in the complex 3-D geometry. Even though the gastric tissue was unable to be tested in this manner, the results from the silicone material showed the highest-stressed area to be at the distal ends of the slit, where a stress concentration due to small radii was formed. As expected, enlarging this radius reduced the stress at this location. It can thereby be recommended from this FEA process that the surgeon reduce stress at the distal ends of the incision by enlarging the radius with the needle knife. Once expanded, the stress levels will likely exceed the elastic region directly next to the ID, but when moving radially, a significant enough reduction is stress will be seen inside the area already damaged by the needle knife that a fracture will not propagate into undamaged gastric tissue.

The most significant findings during experimental validation were the nearly identical results when FEA was compared to these findings. This accomplishes two very important goals. The assumptions used in the FEA computer simulation are validated, which allows for definitive conclusions to be drawn from these simulations. A design engineer can then extrapolate further on the work presented here to allow for more rapid prototype development as it relates to the human gastric tissue. Taking this one step further, different material models – such as the colon or vagina – could be used to discover how these materials respond to similar balloon dilations. Additionally, one could only use the
bench-top experimental model with silicone tissue to quickly test different geometries of incisions or balloons and get usable results, reducing the need for expensive animal testing. It brings the work full circle knowing that either FEA or bench-top simulations are equally capable of predicting stress and strain values in a thin membranous tissue when an incision is under radial dilation.

### 7.3 Recommendations for Future Work

As with any research project, the quest to solve the main goal brings about more questions that were previously not asked and create opportunities for more lines of inquiry. Modern natural orifice surgery has progressed swiftly in the past several years from thoughts and conjecture on possibilities, to human trials and entire divisions in companies devoted to innovating the next generation of minimally invasive tools. The opportunities to contribute to this field are numerous due to the relative infancy of natural orifice research.

As discussed extensively in chapter 2, the material properties of human gastric tissue are not well reported in the literature. Knowing the properties of the materials being encountered by medical devices allows the design engineer the ability to more accurately fit the design to the operating parameters. The work for this dissertation took a very large stride towards defining human gastric tissue, but questions still remain. The first area of skepticism lies in the isotropic assumption. It was shown through this work the material in 0° and 90° are statistically not different from each other. However, there are clearly visual differences in the direction of muscle fibers in the outer layers. How then can the material be isotropic? The material properties of the stomach muscle fibers are not well understood to determine that there should be a significant difference between the two orientations. It would be an interesting study to dissect out only the muscle fibers and test these in 0° and 90° to verify or refute the assumption that there should be differences.

Building on the idea of more accurately determining differences in material properties based on the material orientation, biaxial tensile testing would be able to determine these differences in a single sample. Part of the problem of the current uniaxial testing method,
is once the test sample is cut from the tissue, that area of the stomach cannot also be analyzed in the orthogonal orientation. Therefore, accounting for direction differences assumes the material where the perpendicular sample is cut from is exactly the same as the opposite orientation. Biaxial testing takes a single sample, and pulls equally in 0° and 90° direction and outputs stress values in each direction. This also has the added benefit of allowing for more information for ABAQUS to create a more stable material model.

Furthermore, when samples were prepared for tensile testing, due to the small size needed it was often difficult to ensure the same width of inner and outer layers. Also, because such thin specimens were used, any local anomalies located in the tissue (scar tissue, blood vessels, fatty deposits, etc.) became more relevant to the end results. Testing on a machine capable of larger displacements and loads to allow much larger test samples would be of great interest. By using a larger sample, a more accurate representation of the average bulk tissue properties would be discovered. Additionally, during post-processing of the test data, the width and thickness measurements of the tissue are inputs in an excel macro. The calculated stresses would also be less sensitive to slight inaccuracies in thickness measurements from having a larger sample. The larger samples may also be able to help answer more accurately the previous question about orientation differences.

An area that an entire doctoral dissertation could easily be devoted to is the theory of hyperelastic material models as it relates to ABAQUS. Taking the information of uniaxial and/or biaxial tensile testing, various methods of user subroutines could be programmed to create a more stable material. Instability in the material model was one of the major difficulties encountered during simulation, but while the gastric tissue is quite flexible, it is not as unstable as the computer model currently stands. Programming and developing a user-defined material entails a large effort to ensure accuracy and incorporate it successfully into ABAQUS without problems, but the ability to be able to produce faster simulation times and more accurate results would be greatly beneficial to the field.

In addition to developing a more accurate gastric model, similar models for the colon and vagina tissue would also be quite interesting. It is the author’s opinion that many future NOTES procedures may actually use multiple access points to more accurately provide
traction/countertraction, lighting, visualization, and more suitable surgical angles for many surgeries. The work contained in this thesis could be duplicated for these materials to once again allow for the most accurate designs possible for future medical devices.

Using the more accurately defined material models, a very interesting area of study would be to more closely approximate the FEA simulation to the surgical environment. First, the tissue could be given a thermal damage model necessitating the thermal characteristics of the tissue. Next, the dilation could be represented by the actual dilation of two donut-balloons. The results from this would be interesting to see if the clamping pressure from the balloons can 1) adequately hold the device in place during extreme endoscopic manipulation, and 2) not create too much pressure inducing ischemia near the ID. Also, the stomach is known to be highly vascularized, and the effect of creating the incision in close proximity to blood vessels would also be interesting. Would they alter the deformation in any way? Or would the deformation cause disruption of blood flow? These are just some of the intriguing questions remaining to be answered through more advanced FEA models and accurate physical representations.

Taking all of the information provided through this research, the final step to advancing natural orifice procedures would lie in actual prototyping of the designed devices. Paper designs will not give the surgeon the ability to test and provide constructive criticism to the pros and cons of each. During this prototyping process, it is entirely possible for more ideas to come forth for easier production and better performance than what were previously realized.

Through this research, a large knowledge base has been created in regards to balloon dilating human gastric tissue during natural orifice surgeries. The objective of creating a prototype was achieved through revealing all relevant literature, testing of gastric tissue, experimental validation by a silicone model, and final designs proposed. The work in this thesis provides a backbone for future design engineers to more accurately design medical devices to safely dilate thin membranous tissues for natural orifice and related surgical interventions.
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9. Appendix A

Fundamentally, performing the calculations on an entire assembly is no different than the calculations performed in a very small object, differing only in the size of the matrices involved in the equations. An object is discretized into nodes and elements, where each two nodes are connected via a single element. An example of this can be seen in Figure 9-1 and will be used in the following calculations. Using the assumption that each element behaves as a linear spring, the constitutive force/stiffness equation for each element is created. The local force on each node is equal to the product of this local stiffness matrix and the nodal displacements, Equation 9-1. The local stiffness matrix includes the area, modulus of elasticity, length, and a matrix of displacements in local x and y coordinates, Equation 2-2.

\[
\begin{bmatrix}
1 & 0 & -1 & 0 \\
0 & 0 & 0 & 0 \\
-1 & 0 & 1 & 0 \\
0 & 0 & 0 & 0
\end{bmatrix}
\]

Equation 9-2

Next, a transformation matrix is formed which converts the local orientation of each element into the orientation in the global coordinate system where the angle of rotation is
taken to be positive radians, Equation 9-3. This is then multiplied by the displacement matrix for each node in a single element which appears as Equation 9-4.236

\[
\begin{bmatrix}
\cos \theta & \sin \theta \\
-\sin \theta & \cos \theta
\end{bmatrix}
\]

Equation 9-3

\[
T = \begin{bmatrix}
\cos \theta & -\sin \theta & 0 & 0 \\
\sin \theta & \cos \theta & 0 & 0 \\
0 & 0 & \cos \theta & -\sin \theta \\
0 & 0 & \sin \theta & \cos \theta
\end{bmatrix}
\]

Equation 9-4

A global transformation matrix is formed by combining the products of all the local stiffness and transformation matrices in their appropriate global nodal positions. Using the global transformation matrix, the local forces and displacements are turned into global forces and displacements, Equation 9-5 and Equation 9-6.

\[
U = T * u \quad u = T^{-1} * U
\]

Equation 9-5

\[
F = T * f \quad f = T^{-1} * F
\]

Equation 9-6

These can be rearranged as shown for the local forces and displacements and substituted into Equation 9-1 to form the global constitutive equation, Equation 9-7.

\[
T^{-1} * F = k * T^{-1} * U
\]

Equation 9-7

In an effort to make this equation simpler to calculate and make a global stiffness equation analogous to Equation 9-1, Equation 9-7 is solved for the global force and the transformation matrices and stiffness matrix are combined to form Equation 9-8 which then creates the global constitutive matrix Equation 9-9.
\[ K_G = T \ast k \ast T^{-1} \quad \text{Equation 9-8} \]

\[ F = K_G \ast U \quad \text{Equation 9-9} \]

This equation gives the final positions of the nodal positions with respect to the global coordinate system when forces are acting upon them. The stiffness matrix for each element can be different depending on the boundary conditions applied to each which adds to the complexity of multi-element systems. For example, merely a two-element system has a global stiffness matrix sized 6x6. With a multi-element analysis, the process remains exactly the same, but the global stiffness matrix becomes quite large for even very simple parts.
10. Appendix B

12mm Rigid Object
14mm Rigid Object

Stress of Radially Expanded Tissue Phantom

Legend

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MATLAB Output (A)

ABAQUS Output (B)
18mm Rigid Object

Stress of Radially Expanded Tissue Phantom

MATLAB Output (A)

ABAQUS Output (B)
11. Appendix C

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<tr>
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<td>Length</td>
</tr>
<tr>
<td>400</td>
<td>Drilled to be capped for G3 screws</td>
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Drilled to be capped for G3 screws.
A FRONT PLATE

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</table>

**NOTATION AND CONVENTIONS**

- 6-32 screws through holes for larger holes are through holes for 0.25 peg.
- Smaller holes are through holes for 0.25 peg.

Dimensions:
- 0.26
- 0.30
- 0.450
- 0.50
- 6.00
- 3.00
- 2.00
- 0.00

**Construction Details**

- [Diagram with dimensions and notes]
A Back Plate

Bottom three holes drilled and tapped for 6-32 screws.
off a bill
edge, knock the edge
Non-official chamfered

Drilled and tapped for
6-32 screws

Sure screw heads will
just enough to make
non-official depth.

Hold.

---

1.25

75