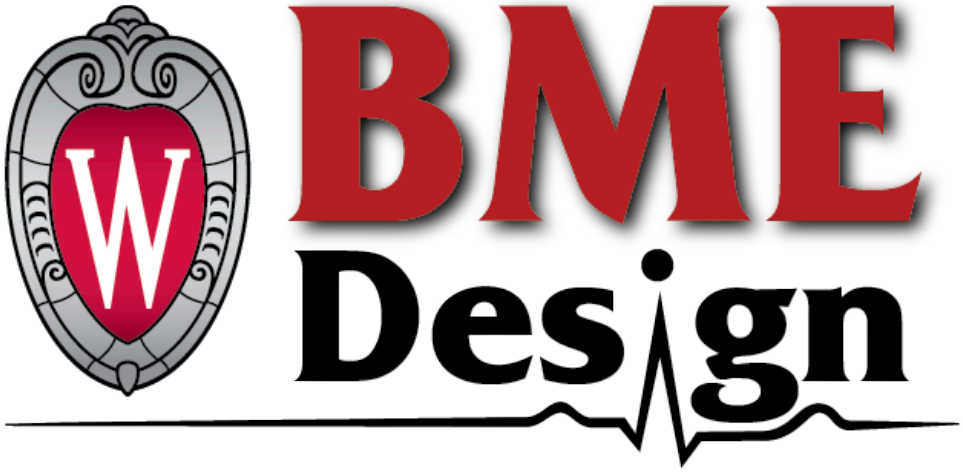

Biodegradable Coating to Improve Administration of Endoscopic Negative Pressure Therapy

Final Report

BME 301

April 29, 2026

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Abstract

Esophageal anastomotic leaks are a serious complication after gastrointestinal surgery, occurring in up to 40% of cases and often leading to high morbidity of patients. Endoluminal vacuum (EndoVAC) therapy has emerged as an effective minimally invasive treatment where continuous negative pressure is applied to promote healing. Despite its success, the procedure is difficult to perform due to its labor-intensive placement and reliance on endoscopic manipulation skill, which limits its widespread use. To address this issue, this project developed a biodegradable coating designed to promote easier delivery of EndoVAC sponges. The device compresses a polyurethane sponge with a degradable coating that maintains a small size during insertion and dissolves once in the body, allowing the sponge to expand in the cavity and function normally. As a coating materials, gelatin hydrogel/film, and crosslinked sodium alginate were tested under physiological conditions to evaluate degradation time and sponge expansion. Testing showed that gelatin hydrogel dissolved too quickly, while gelatin film and sodium alginate remained stable over the required 15 minutes deployment requirement. Gelatin-coated sponges were fully expanded within 20 minutes, but expansion began earlier than desired. Sodium alginate performed slower and more controlled degradation. These results prove that biodegradable coatings can improve the efficiency of EndoVAC treatment. With further optimization, particularly of sodium alginate, this approach could increase accessibility of the treatment in clinical settings.

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Introduction

1.1. Motivation

Esophageal anastomotic leaks are the result of gaps in the anastomosis, staple lines, or tract of the esophagus [1]. Leaks are reported in up to 40% of esophagectomies and contribute to the high morbidity and mortality rates of the procedure [2] [3]. Patients that are of male gender, have a body mass index greater than 30 kg/m^2 or less than 18.5 kg/m^2 , have diabetes or undergoing prolonged operation time are at greater risk [4]. Diagnosis is challenging because presentation ranges from asymptomatic to sepsis with multi-organ failure, so postoperative imaging, inspection of surgical drains, and patient monitoring is crucial [4]. Following diagnosis, the course of treatment is tailored to the patient and involves endoscopic surgery followed by rescue surgery, if needed [5]. Recently, surgeons have been utilizing endoluminal vacuum (EndoVAC) therapy by placing negative pressure devices, traditionally used for external wounds, in the gastrointestinal (GI) tract. EndoVAC therapy promotes healing by the macrodeformation and microdeformation of the cavity, increasing perfusion, removing fluid, and clearing bacteria [6]. This method of treatment has an 80% success rate in the upper GI tract, but is limited by the complexity and labor intensive nature of the procedure [6].

1.2. Existing devices and Current Methods

Management of esophageal leaks has traditionally involved endoscopic repair methods such as endoclips, suturing systems, tissue sealants, and self-expanding metal stents (SEMS), with surgical reoperation being reserved for the most severe cases [7]. EndoVAC therapy has been a more successful and less invasive option. It consists of an open-pore polyurethane sponge placed endoscopically at the defect site and connected to an external vacuum source, applying continuous negative pressure to promote granulation tissue formation, evacuate infectious fluid, and enhance local tissue perfusion until closure is achieved. Boston Scientific offers two commercially available devices: the Eso-SPONGE™, designed for upper gastrointestinal leaks and perforations, and the Endo-SPONGE™, primarily indicated for colorectal anastomotic leaks [8] [9]. These products rely on large, rigid overtubes that are difficult to manipulate into the cavity, especially in cases where the leak site is an irregular shape. Instead, surgeons choose to assemble a device by manually trimming polyurethane foam and suturing it to a nasogastric or surgical drain tube [10]. This approach lacks standardization, introduces variability, and is labor intensive.

1.3. Problem Statement

Anastomotic leaks can cause severe complications, and traditional treatment methods can be invasive and result in extended hospitalization. EndoVAC therapy has proven to be a successful treatment of defects in the upper GI tract. However, use is labor intensive and placement requires skill to manipulate an endoscope. These challenges prevent the therapy from becoming widespread, so a solution is needed to make EndoVAC deployment more efficient.

Background

1.4. Background Research

Anastomosis is a surgical technique used to reconnect two ends of a hollow structure, such as the esophagus, stomach, or intestine, after a diseased or damaged tissue segment has been removed. Procedures such as esophagectomies and gastrectomies require this reconnection to restore passageway through the digestive tract, allowing the patient to eat and digest normally. Despite advances in surgical technique, the joined tissue can fail to heal properly, resulting in an anastomotic leak. This occurs when the surgical connection breaks down and the contents of the gastrointestinal tract, including digestive fluids, bacteria, and food, escape into the surrounding body cavity. The consequences are severe, causing local infection and inflammation which can rapidly spread and lead to sepsis, organ failure, and, in worst cases, death. Anastomotic leaks are reported in up to 40% of esophagectomies and up to 17% gastrectomies, representing one of the most serious complications in upper gastrointestinal surgery [2]. Traditionally, managing these leaks required invasive reoperation to repair or divert the leak, carrying significant additional risk for patients who are already in a fragile state [2].

The challenge is compounded by anatomy. In the esophagus, for example, the anastomosis sits in the chest, immediately adjacent to the heart and lungs. A leak in this location means that contaminated fluid and bacteria can enter the mediastinum (the central chest cavity) putting critical structures at risk. Open surgery to access this region is dangerous and demanding for the surgeon, making minimally invasive alternatives favorable.

This is where endoscopic vacuum therapy has emerged by offering a compelling alternative to reoperation and higher success rates. Rather than surgically re-entering the body, a flexible endoscope is guided through the mouth and down into the digestive tract to place a small open-pore sponge directly at the site of the leak. The sponge is connected to an external vacuum pump via thin drainage tubing and once placed will undergo continuous suction. Because granulation tissue gradually grows into the sponge and debris can accumulate within the pores, the sponge is typically exchanged every three to seven days to prevent clogging and excessive tissue ingrowth [11]. It takes 35.8 days, on average, for the defect to show sufficient closure, so 7.2 foam change procedures are required [12].This set up works well due to several aspects: the suction continuously evacuates the contaminated fluid, the pressure mechanically reduces the cavity size by drawing the walls inward while also promoting the formation of new, vascularized tissue. These effects convert an infected cavity into a clean, healing wound. Despite favorable closure rates, the therapy remains resource intensive. Each sponge exchange requires repeat endoscopy, procedural sedation or anesthesia, and coordination with inpatient care. Reported complication rates include rare instances of bleeding particularly in prolonged therapy courses [12].

1.5. Design Research

Design improvements for endoluminal vacuum therapy will focus on enhancing procedural efficiency, ensuring mechanical suction reliability, and maintaining long-term biocompatibility within the gastrointestinal environment.

Material science research is essential to identify biocompatible, lightweight materials that are safe for endoscopic delivery while remaining mechanically strong enough to withstand continuous negative pressure and the intrinsic compressive forces of the esophageal wall. The selected materials must maintain

structural integrity for up to seven days within the gastrointestinal environment without degradation, loss of mechanical strength, or functional obstruction of the drainage pathway. It is necessary to prevent deformation or collapse that could compromise suction efficiency. Additionally, material surfaces should not promote excessive tissue adhesion that would interfere with removal or healing.

Current placement techniques can be complicated and involve multiple procedural steps. Therefore, research should prioritize simplified deployment mechanisms that reduce complexity and minimize required techniques. The design needs to allow efficient insertion, accurate positioning, and controlled removal to improve procedural speed and efficiency. Reducing technical burden is critical not only for workflow efficiency but also for minimizing tissue trauma during placement and exchange.

Additional considerations include sterilization compatibility, mechanical integrity under suction loading, and safe integration with flexible endoscopes and suction systems.

1.6. Client Information

Dr. Amber Shada is a UW Health general surgeon and an associate professor at the University of Wisconsin School of Medicine and Public Health in the Department of Surgery. Dr. Shada specializes in minimally invasive surgery and treats issues involving the digestive system.

1.7. Product Design Specifications

The design must be used to place a V.A.C Grandufoam Dressing (polyurethane sponge) within a leakage cavity in the gastrointestinal tract and sustain negative pressure. An average esophagus has a diameter of 2.0-3.0 cm, limiting the combined diameter of design components to smaller than 2.0 cm. The size of the defect can range from 2.0-15.0 cm. This means that the design must be able to deliver a sponge from 1.0-10.0 cm in diameter either intraluminally or intracavity to effectively promote wound closure when negative pressure is applied. Negative pressure will be applied at a constant rate of 125mmHg-175mmHg for 3-7 days. All materials used to fabricate the device must be able to withstand constant negative pressure and allow for removal from the patient every 3-7 days. The device will be implanted in the gastrointestinal tract with an average temperature of 36-38°C, a pH of 1.5-3.5 in the stomach, and a pH of 7.0 in the esophagus. Under these conditions, the materials used must be biocompatible to prevent an adverse immune response. Biocompatibility requires that the materials are compliant with the ISO standards pertaining to biomaterials and the interaction of devices with intact and compromised tissue. Given the prolonged contact with mucosal tissue, the materials used must not result in infectious or toxic effects on the biological system required by ISO 10993. Potential risks and risk management will be addressed using ISO 14971 to estimate the probability of occurrence of harm and the consequences of such harm. Lastly, the device will be applied endoscopically. ISO 8600 defines the requirements for endotherapy devices used in medicine. Refer to Appendix I for more details on the product design specifications.

Preliminary Designs

1.8. Design 1: Balloon Stent Design

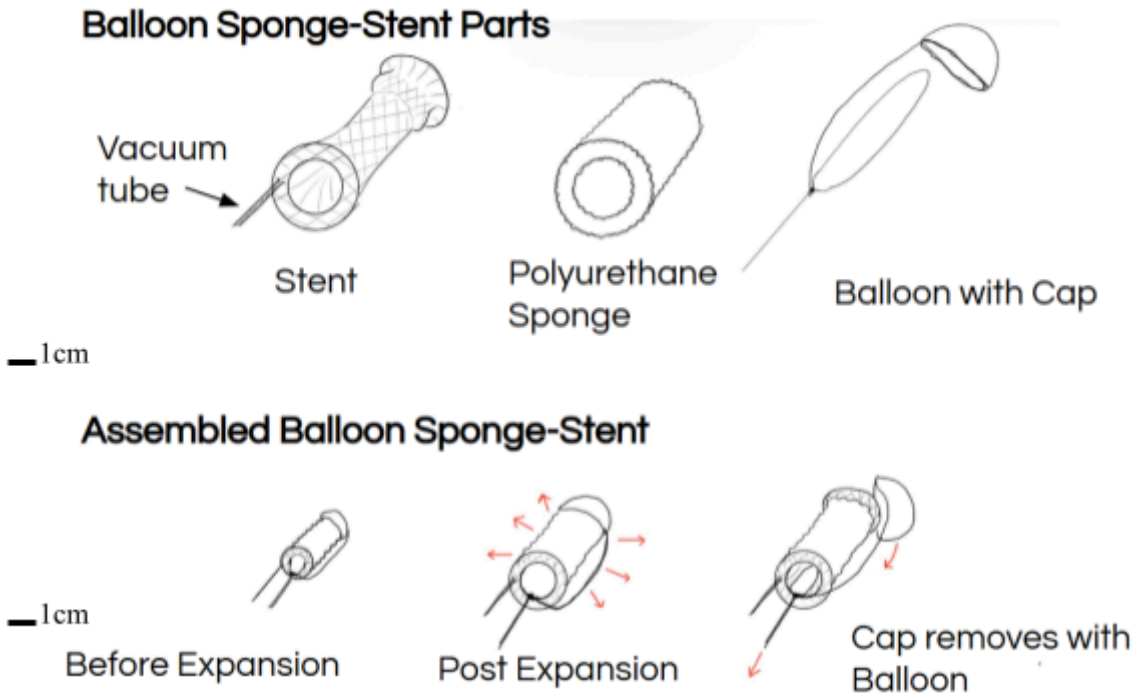

Figure 1: Drawing of the Balloon Stent Design components and deployment. Assembled components would be inserted into the esophagus and upon proper placement the balloon is expanded. The cap and balloon are then removed, leaving the stent in place.

This design is composed of three main components: A stent backbone, a polyurethane sponge and an inflatable balloon with a protective cap. During insertion, the unexpanded stent is covered by the cap, which shields surrounding tissue from the sponge facilitating an easier insertion process to the defect cavity. Once positioned, the balloon is inflated to expand the stent, and both the balloon and cap are removed together. The expanded stent creates a seal between the GI tract and the leak cavity, providing structural stability that guides fluid removal while allowing patients to eat normally during the course of treatment.

1.9. Design 2: Degradable Coating Design

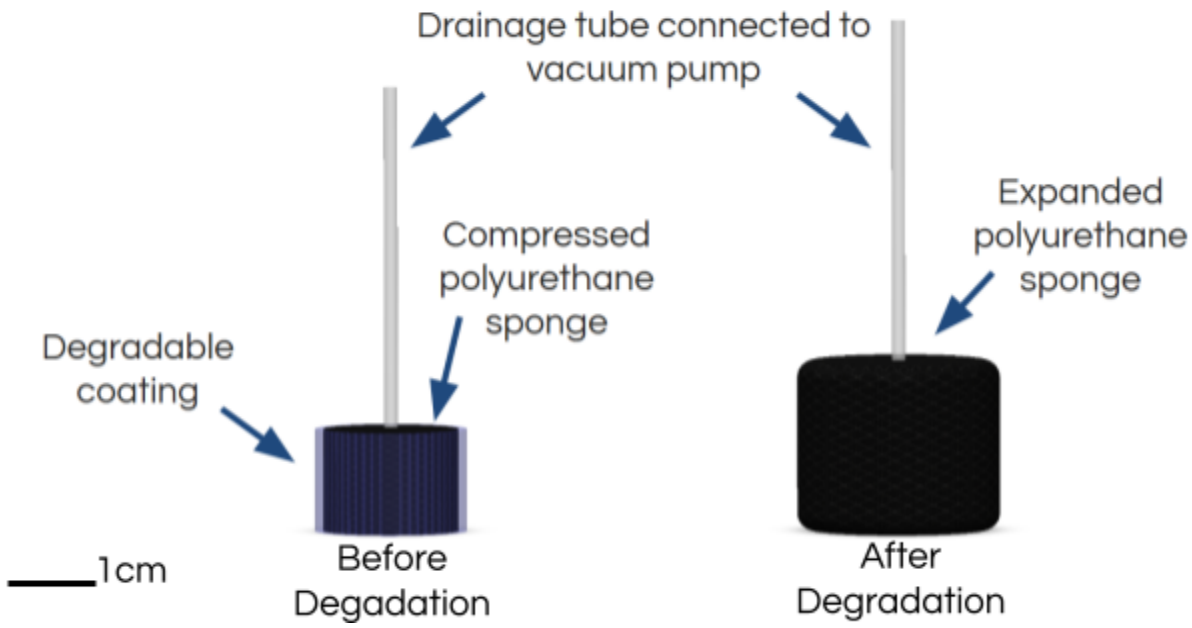

Figure 2: During deployment of the Degradable Coating Design, the degradable coating is intact and holding the sponge at a smaller size (left). After proper placement, the coating dissolves and the sponge expands (right).

This design includes a biodegradable coating that will encapsulate the polyurethane sponge upon delivery in the gastrointestinal tract. The coating will provide an oxygen barrier to prevent expansion of the sponge. Negative pressure will be used to compress the sponge and then it will be sealed using an impermeable biomaterial. Once the biomaterial is degraded in the intraluminal cavity, compressive stress will be reduced and the sponge will be exposed to air. These events allow the sponge to expand and fill the cavity. Negative pressure can then be applied to drain and close the cavity.

1.10. Design 3: Cap Delivery Design

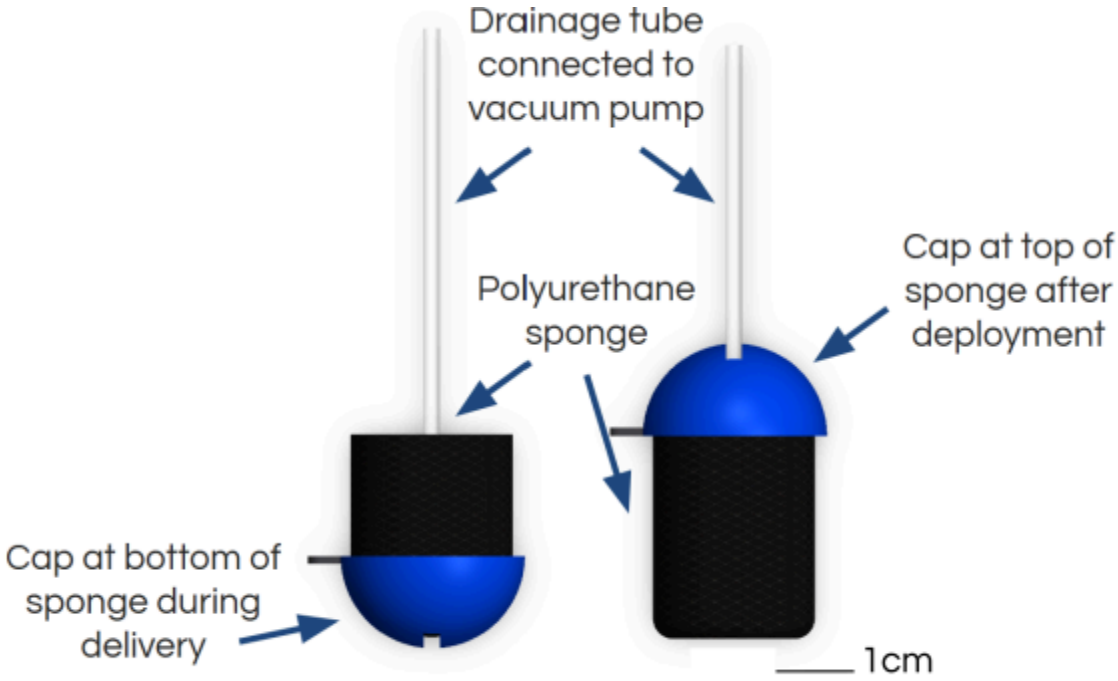

Figure 3: During deployment of the Cap Delivery Design, the cap minimizes the insertion size of the sponge. Upon placement, the cap is pulled back to allow contact between the sponge and cavity. The cap will remain inside the cavity with the sponge to aid in removal.

The Cap Delivery Design features a biocompatible, cross-slit plastic cap designed to optimize both the delivery and removal phases of the procedure. During the initial insertion, the cap serves as a protective housing that compresses the polyurethane sponge, facilitating a significantly smoother passage through the esophagus. Once the device reaches the target site, the sponge is pushed through the cross-slit cap to be deployed into the cavity and the sponge expands, effectively filling the cavity while maintaining negative vacuum pressure through the integrated drainage tube. The cap remains positioned behind the sponge until the replacement. This cap placement helps replacement, acting as a guide for easy and safe removal of the sponge from the patient.

Preliminary Design Evaluation

1.11. Design Matrix

Table I: Preliminary Design Matrix

Criteria	Weight	Balloon Sponge Stent		Degradable Coating		Cap Delivery	
Safety	**17.5**	3/5	10.5	**4/5**	**14**	3/5	10.5
Ease of Placement	**17.5**	3/5	10.5	**4/5**	**14**	3/5	10.5
Ease of Removal	**15**	2/5	6	**4/5**	**12**	3/5	9
Ease of Fabrication	**15**	2/5	6	3/5	9	**4/5**	**12**
Patient Comfort	**15**	**4/5**	**12**	3/5	9	2/5	6
Adjustability	**10**	2/5	4	**4/5**	**8**	3/5	6
Cost	**10**	2/5	4	3/5	6	**4/5**	**8**
Total (100)	**100**	53/100		**72/100**		**62/100**	

The degradable coating ranked the highest overall within the design matrix due to safety, ease of placement, ease of removal, and adjustability. The degradable coating design features a compressed sponge that is surrounded by a biomaterial that will degrade within the gastrointestinal leak cavity. The biocompatibility of the design and lack of rigid pieces contribute to the highest safety rating. There is decreased risk in parts being dislodged from the design or being stuck within the gastrointestinal tract. Ease of use was an important consideration provided by the client. The degradable coating rated highest in both the ease of placement and the ease of removal. With a simple design and a coating providing lubrication, placement of the design is streamlined. However, the potential for a narrow window of adjusting the placement position could result from rapid degradation of the coating. Similarly, removing the device involves fewer parts that could get caught and stuck in the gastrointestinal tract. The only force counteracting the pull-out force will be the friction of the sponge. During the procedure, the sponge is cut to size to fit within the leakage cavity. The degradable coating design can be applied to sponges of any size, contributing to the high degree of adjustability. More details on the criteria rankings and competing designs can be found in Appendix II.

Proposed Final Design

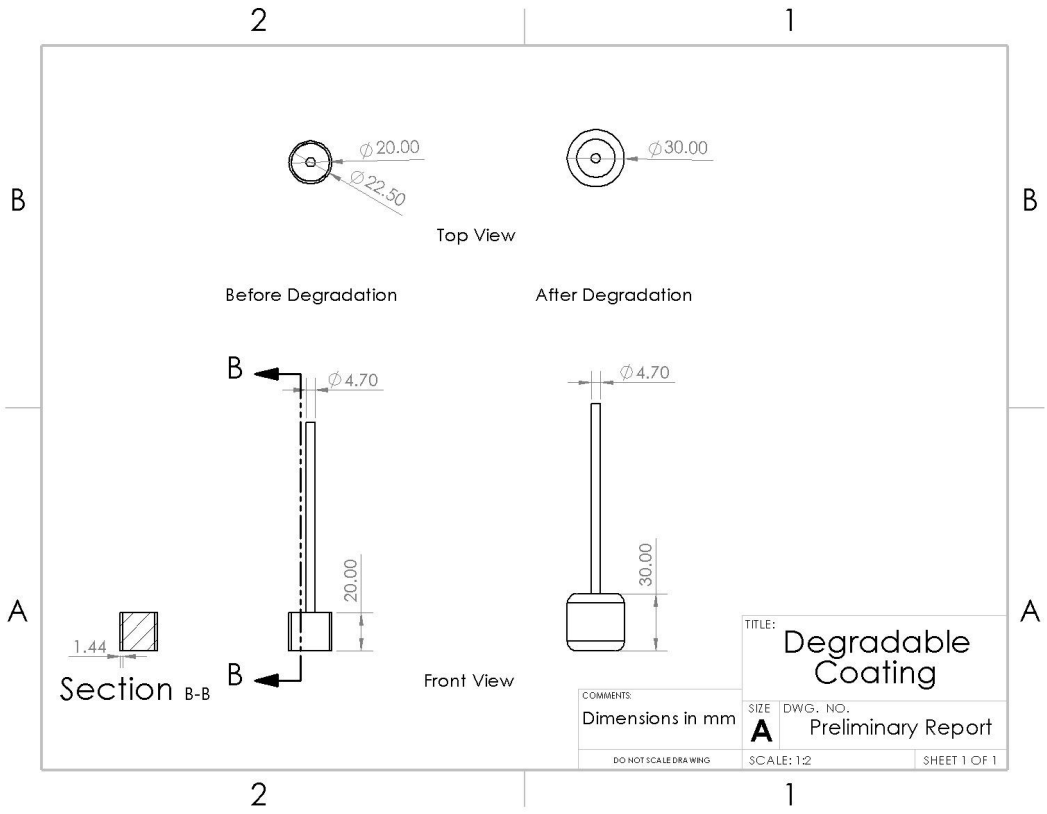

Figure 4: SolidWorks technical drawing of the Degradable Coating Design.

The proposed final design is the degradable coating design. The design won 4 of the 7 criteria in the design matrix, including the most heavily weighted criteria in safety, ease of placement, and ease of removal. Therefore, it is expected to be the best design based on the defined criteria. Prior to fabrication, the material used for the degradable coating will be determined.

Sponge Mold Design

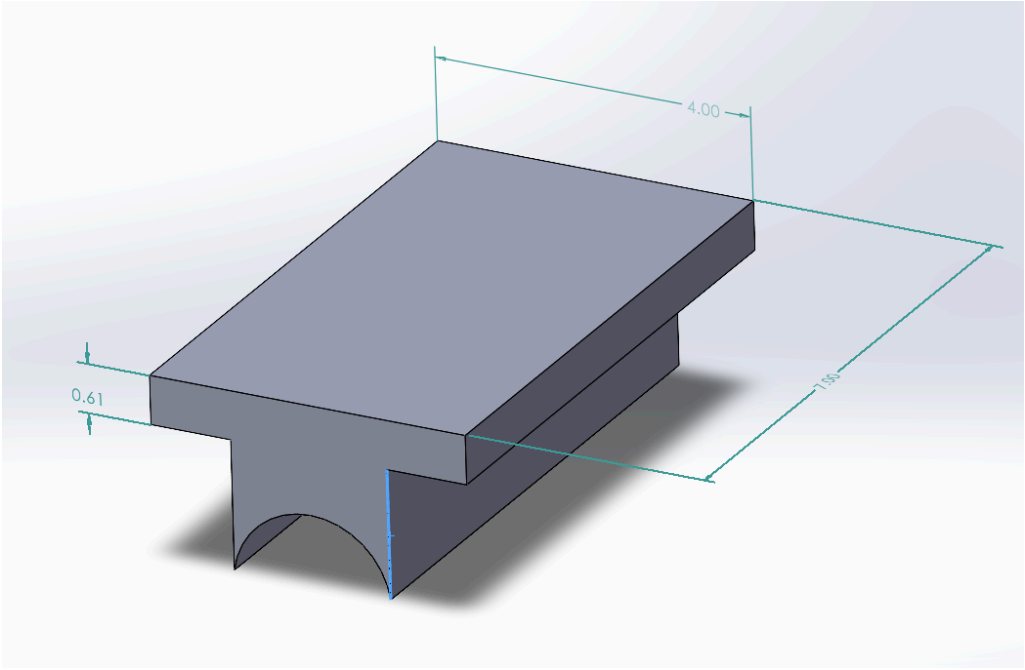

Figure 5: CAD model for the top piece of the compression mold. (dimensions in cm).

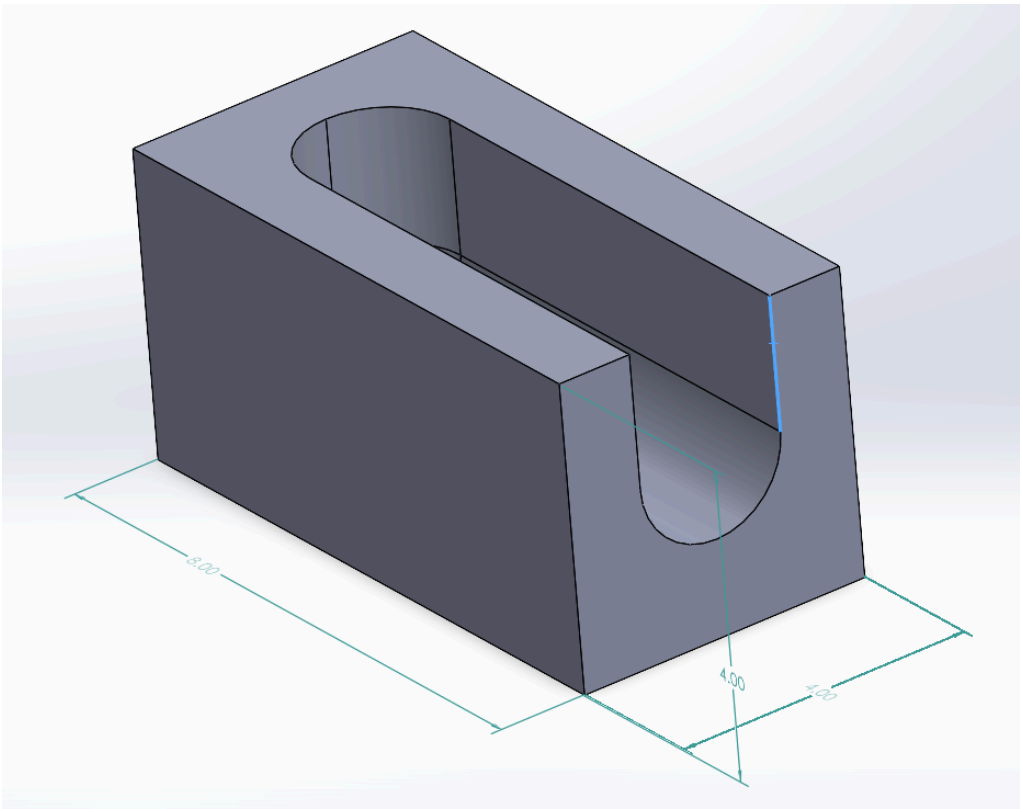

Figure 6: CAD model for the bottom piece of the compression mold (dimensions in cm).

The final design of Sponge Mold consists of two primary components to achieve material compression with precise dimension: a top part and a bottom part. The mold operates by placing sponge onto a material within the bottom part, followed by integration of the top part that applies uniform compression. The end of the terminal is designed spherically to ensure easier delivery of the compressed sponge with minimized friction. While maintaining the standardized outer dimension, the compression channels offer four diameters: 1.0 cm, 1.5 cm, 2.0 cm, and 2.5 cm. The molds were fabricated using 3D printing with TPU, PETG, and PLA for materials' mechanical characterization. Refer to Appendix III for the SolidWorks technical drawing of the molds.

Fabrication

1.12. Materials

All materials used were provided by the client or were available in the teaching lab. Refer to Appendix IV for the full expense spreadsheet.

1.12.1. EndoVAC

The client has provided us with polyurethane sponges, nasogastric tubes, and sutures to construct the EndoVAC device.

The polyurethane sponge was from a V.A.C. GranuFoam Dressing kit. The sponge has a 400-600 micron open pore structure to ensure equal negative pressure across the wound and is hydrophobic to promote fluid removal [13].

The nasogastric tube was the Salem Sump Tube in size 14Fr/Ch (4.7mm) x 48in. It will be attached to the vacuum device and provide negative pressure to the esophageal defect through the sponge. The sponge was sutured to the tube using size 3-0 ETHILON Nylon Suture.

1.12.2. Degradable Materials

Gelatin is a biocompatible and degradable material made of denatured collagen protein [14]. In fabrication, type A porcine gelatin from Sigma Aldrich was used. Type A gelatin is derived with partial acid so its isoelectric point is at pH 7, making it ideal for degradation in the esophageal environment [15].

Sodium alginate is a biocompatible and biodegradable material extracted from the cell wall of brown seaweed [16]. In fabrication, Keltone LV/NF from FMC Biopolymer was used. Calcium chloride was used to reversibly crosslink the sodium alginate [14].

Molds were 3D printed to allow sponge compression while the degradable coating was applied. Polyethylene terephthalate glycol (PETG) was used because it has heat resistance of 69°C, so it could withstand the coating process [17]. Label tape was used to hold the mold pieces together during coating.

1.13. Methods

1.13.1. Suturing Sponge to Nasogastric Tube

The negative pressure dressing and suction device was prepared using a nasogastric tube, a polyurethane sponge, and nylon sutures. First, the sponge is cut to a desired length and diameter using surgical scissors. Next, the scissors are used to form a hole through the center of the sponge cylinder. The nasogastric tube is threaded through the sponge until each side port is fully covered. Finally, a running suture technique is used to tie the sponge to the nasogastric tube.

1.13.2. Gelatin Preparation

Gelatin solution was prepared by dissolving gelatin powder and glycerin in distilled water to produce a homogenous solution. The solution was then cast into petri dishes. Hydrogels were produced by leaving the dishes covered to set. Films were made by leaving the dishes uncovered to set. See Appendix V for full fabrication protocol.

1.13.3. Sodium Alginate Preparation

Sodium alginate films were prepared by dissolving sodium alginate powder and glycerin in distilled water to produce a homogeneous solution, which was then cast into petri dishes and dried in an oven at 60°C for 24 hours. Crosslinking was achieved by submerging the dried films in a 0.8 M calcium chloride ($CaCl_2$) solution for 2 minutes. Divalent Ca^{2+} ions diffused into the alginate matrix and formed ionic crosslinks between guluronate residues on adjacent polymer chains via the egg-box binding mechanism, in which Ca^{2+} ions are coordinated within cavities formed by pairs of opposing guluronate sequences, physically crosslinking the hydrogel network [18]. The degree of crosslinking is directly influenced by $CaCl_2$ concentration, whereby higher concentrations result in faster gelling time, increased gel strength, and greater water expulsion from the gel network due to a proportional increase in Ca^{2+} interaction with alginate chains [18]. For fill fabrication protocol, see Appendix VI.

1.13.4. Coating Compressed Sponge

Coated sponges were fabricated by first suturing a sponge, cut to size, on the nasogastric tube. A piece of gelatin was then set in the bottom portion of the mold. A sponge was manually squeezed and set in the mold, on top of the gelatin. Then, the top piece of the mold was used to compress the sponge and gelatin to a diameter of 1.5cm. The mold was secured with label tape and put into an oven at 50℃ to soften the gelatin. The mold was then placed upright in the fridge to set. When the sponge is removed from the mold it will have a gelatin hydrogel coating. To produce a film, it must be left out to dry after setting in the fridge. See Appendix VII for full fabrication protocol.

1.14. Final Prototype

Figure 7: Final prototype of gelatin encapsulating polyurethane sponge.

The final prototype features a 3.0 cm diameter polyurethane sponge, compressed using a gelatin film. After compression was applied using a 1.5 cm diameter mold, the final delivery device is 1.5 cm in diameter with the sponge and gelatin film. The device is inserted orally into the esophagus. This decreased diameter ensures compatibility with the esophageal lumen and reduces insertion force,

minimizing potential mucosal damage. Once inside the esophagus, physiological conditions promote melting and degradation of the gelatin, releasing the sponge and allowing sponge expansion.

The polyurethane sponge is 7 cm in length and sutured to a 14 F nasogastric tube with a nylon suture. Side ports on the nasogastric tube allow for negative pressure to be applied to the sponge once placed in the esophageal cavity. The length of the sponge is required to cover the side ports on the distal end of the nasogastric tube. When negative pressure is applied, the sponge will shrink, pulling in the walls of the leak, promoting tissue granulation and wound closure. The device can then be removed by withdrawing the nasogastric tube, allowing for periodic replacement as required in EndoVAC therapy.

Testing and Results

1.15. Degradation Testing

A key requirement of the degradable coating design is that the biodegradable film must dissolve within the esophageal tract within a clinically acceptable deployment window. During delivery, the coating encapsulates and compresses the sponge, maintaining it in a reduced profile for safe endoscopic insertion. Once insertion begins, the coating must remain structurally intact throughout the full deployment procedure, which encompasses passage of the device through the oral cavity and esophagus to the anastomotic leak site. The surgeon must have a minimum of 15 minutes before coating dissolution begins and the sponge expands, allowing sufficient time to confirm placement and establish the negative pressure connection.

Both candidate coating materials were evaluated: gelatin films and sodium alginate crosslinked with calcium chloride. For gelatin, two preparation conditions were compared. Covered gelatin, in which samples were set with a lid to retain moisture, producing a soft hydrogel-like film, and uncovered gelatin, in which samples were set without a lid, allowing moisture to escape and producing a thin dried film. These two conditions were tested to determine whether the physical state of the gelatin film influences its degradation rate, and to identify which preparation method is more suitable for the coating application. Sodium alginate crosslinked with calcium chloride was tested as a second independent candidate material. Degradation testing across all three conditions was performed to characterise mass loss over time and determine whether either material meets the deployment time specification under simulated physiological conditions.

All samples were immersed in 1X phosphate buffered saline (PBS, pH 7.4 ± 0.2, prepared by diluting 10X PBS stock solution 1:9 with distilled water) to replicate the pH of the esophagus at the site of device deployment. Samples were maintained at 37 ± 1°C throughout testing using an incubator to replicate average body temperature. Solution pH and temperature were verified at 0, 15, 30, 60, and 90 minute intervals using pH strips and a temperature probe to confirm that conditions remained within the physiological range across the full testing period. Six replicates were tested per condition. Each sample was placed in an individual container with a minimum PBS volume of ten times the sample mass to ensure degradation products did not accumulate and alter the local environment between measurements. Samples were removed from solution at time points of 0, 5, 10, 15, 20, 25, 30, 35, 40, 45, 60, and 90 minutes, blotted gently

using a standardised blotting procedure to remove surface moisture, and immediately weighed on a calibrated scale. For gelatin samples, weighing continued at 100 minutes until complete dissolution was confirmed. Percentage mass remaining relative to initial mass at t = 0 was calculated for each sample at each time point. See Appendix VIII for testing protocol.

Percentage mass remaining over time will be plotted for each of the three conditions to generate degradation profiles. A material that meets the deployment specification should demonstrate substantial or complete mass loss within approximately 30 minutes under these conditions. Comparison between covered and uncovered gelatin will indicate whether moisture content during preparation significantly affects degradation rate, informing which gelatin preparation method is more appropriate for the coating application. Comparison between gelatin and sodium alginate will indicate which candidate material more closely meets the deployment time requirement, and will guide material selection for further design development. If neither material degrades within the required window, the results will inform what modifications may be needed (such as adjusting film thickness, gelatin concentration, or crosslinking density) before further testing is conducted.

1.16. Degradation Results

1.16.1. Covered Gelatin

Covered gelatin dissolved immediately upon immersion in PBS at 37°C, precluding any gravimetric data collection. Complete dissolution was observed within the first measurement interval for all six samples. This behaviour is consistent with the high moisture content retained during the covered setting process, which produced a hydrogel-like film with a high degree of water activity and minimal structural integrity when exposed to an aqueous environment. As a result, no degradation profile could be generated for this condition.

1.16.2. Uncovered Gelatin

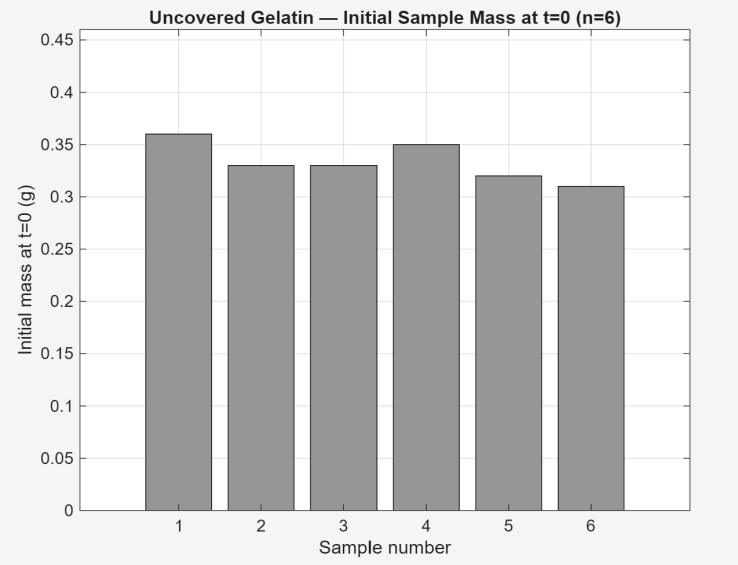

Figure 8: Uncovered gelatin initial sample masses

Initial sample masses were consistent across all six replicates, ranging from approximately 0.31 g to 0.36 g, indicating that gelatin films were prepared with reasonable uniformity prior to testing.

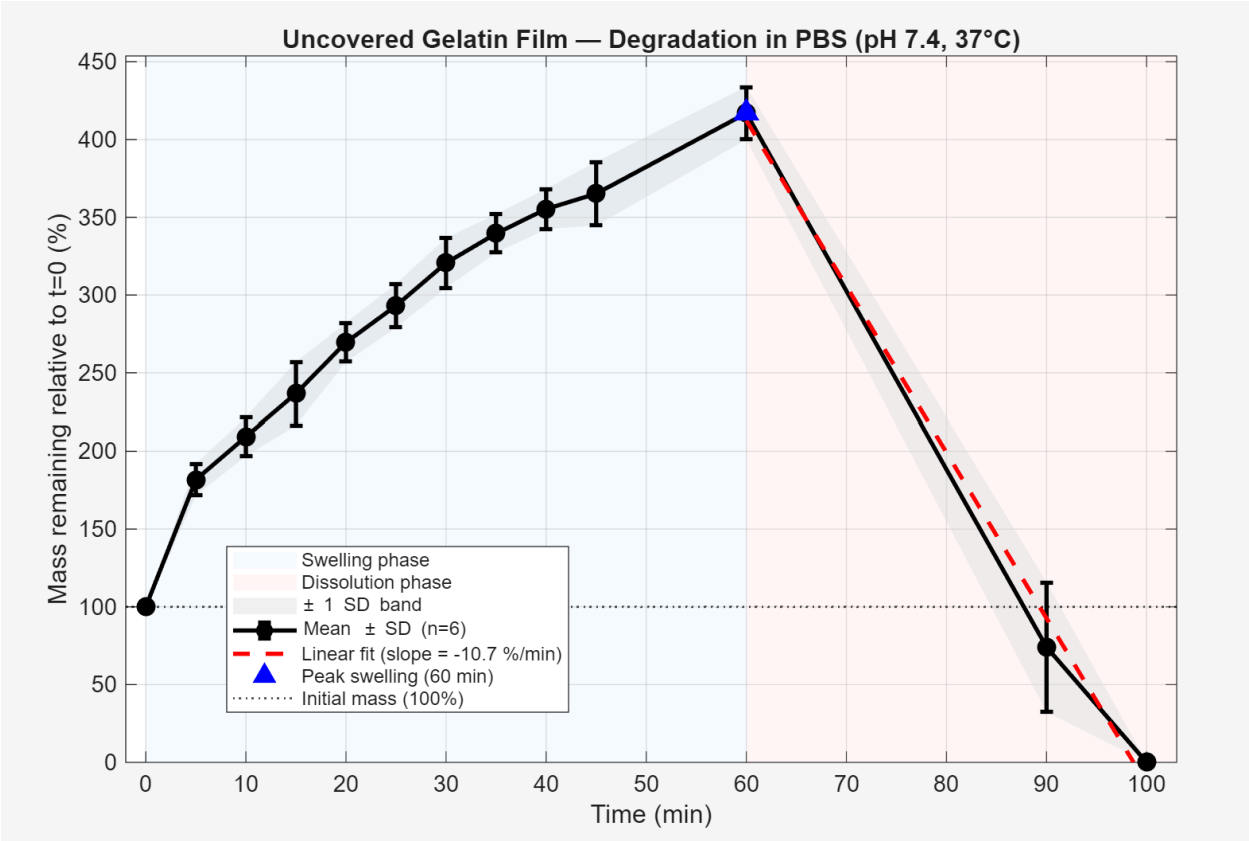

Figure 9: Degradation plot of uncovered gelatin films.

Uncovered gelatin demonstrated the most pronounced swelling, with mean mass increasing to 417% of initial mass by 60 minutes as the dried film absorbed PBS. Following this peak, rapid dissolution occurred and complete mass loss was confirmed for all six samples between 90 and 100 minutes. The dissolution phase followed a linear mass loss profile with a slope of -10.7 % per min, indicating a fast and consistent dissolution rate once degradation began. See Appendix IX for MATLAB code.

1.16.3. Sodium Alginate

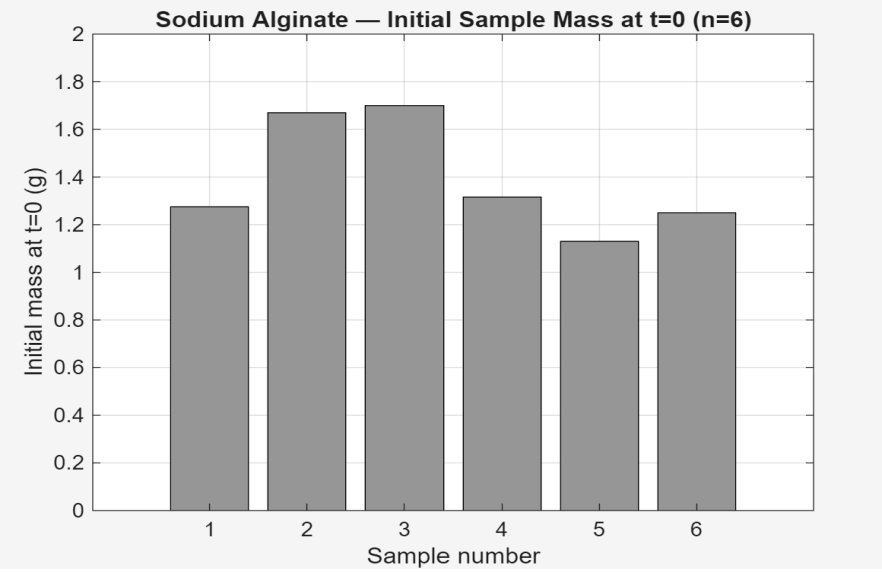

Figure 10: Sodium Alginate initial sample masses

Initial sample masses varied across replicates, ranging from approximately 1.17 g to 1.69 g, representing a substantial difference between the lightest and heaviest sample. This variation in sample mass likely reflects inconsistencies in the manual crosslinking and preparation procedure, and may have contributed to the substantial inter-sample variance in degradation rate observed across the testing period.

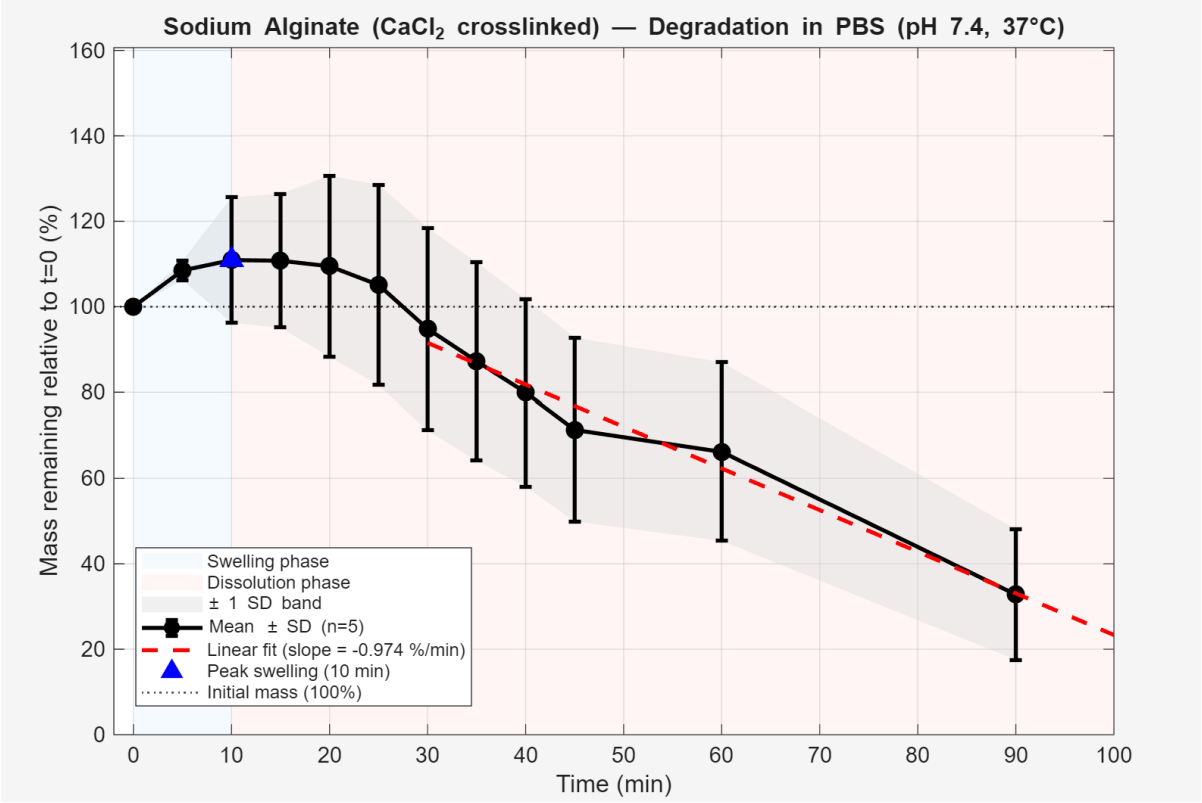

Figure 11: Degradation plot of Sodium Alginate. Estimated time to dissolution is 124 minutes.

Sodium alginate showed markedly different behaviour. Initial swelling was minimal, with mean mass reaching a peak of approximately 111% of initial mass at 10 minutes, indicating limited water absorption compared to gelatin. Mass then declined gradually and linearly from approximately 30 minutes onwards. One sample (Sample 1) was excluded from analysis as an outlier, as its mass remained near-constant across the full 90 minute testing period, consistent with anomalously high crosslink density relative to the other replicates. Analysis of the remaining five samples yielded a dissolution phase slope of -0.974 % per min. Complete dissolution was not observed within the 90 minute testing window, with mean mass remaining at approximately 33% at 90 minutes. Extrapolation of the linear fit estimates complete dissolution at approximately 124 minutes. Substantial inter-sample variance was observed throughout, reflected in large standard deviations at each time point, attributed to uneven crosslinking during sample preparation, as seen in the figure below. See appendix IX for MATLAB code.

1.17. Sponge Expansion Testing

A key performance requirement of the coated sponge design is that, following coating dissolution, the sponge must reliably expand to its original diameter at the anastomotic leak site. Per design requirements, the sponge should remain intact for at least 15 minutes to allow sufficient deployment time for the surgeon. However, if the sponge fails to fully re-expand,

contact with the wound bed may be incomplete, compromising treatment outcomes. Expansion testing was therefore conducted to characterise the re-expansion behaviour of gelatin-coated sponges under simulated physiological conditions and to assess whether the coating impedes or alters the final expanded geometry of the polyurethane sponge.

Six polyurethane sponges of approximately 3 cm initial diameter were compressed with a custom made 3D printed mold to a reduced profile of approximately 1.5 cm and encapsulated in a gelatin coating, which was allowed to dry to a rigid film. This compressed and coated configuration represents the intended delivery state of the device. Each coated sponge was submerged individually in 400 mL of 1X phosphate buffered saline (PBS, pH 7.4 ± 0.2, prepared by diluting 10X PBS stock solution 1:9 with distilled water) within a 500 mL beaker to replicate the pH of the esophagus at the deployment site. Solution temperature was maintained at 37 ± 1°C using hotplates to replicate average body temperature, with stir bars operating at 100 rpm to promote convective mixing and prevent localised accumulation of dissolution products. A standardised backdrop and tripod-mounted camera were used to record each sponge independently via time-lapse video. Frames were extracted at approximately one-minute intervals and sponge diameter at each time point was quantified from the images using ImageJ software, with the recording timeline back-calculated to assign accurate timestamps to each frame.

Sponge diameter was recorded at each time point from t = 0 minutes until full expansion was confirmed, with the initial compressed diameter and the final expanded diameter measured directly using a caliper. Percentage expansion relative to initial compressed diameter was calculated at each time point for all six replicates and plotted over time to characterise the rate sponge expansion. See Appendix X for the testing protocol.

1.18. Sponge Expansion Results

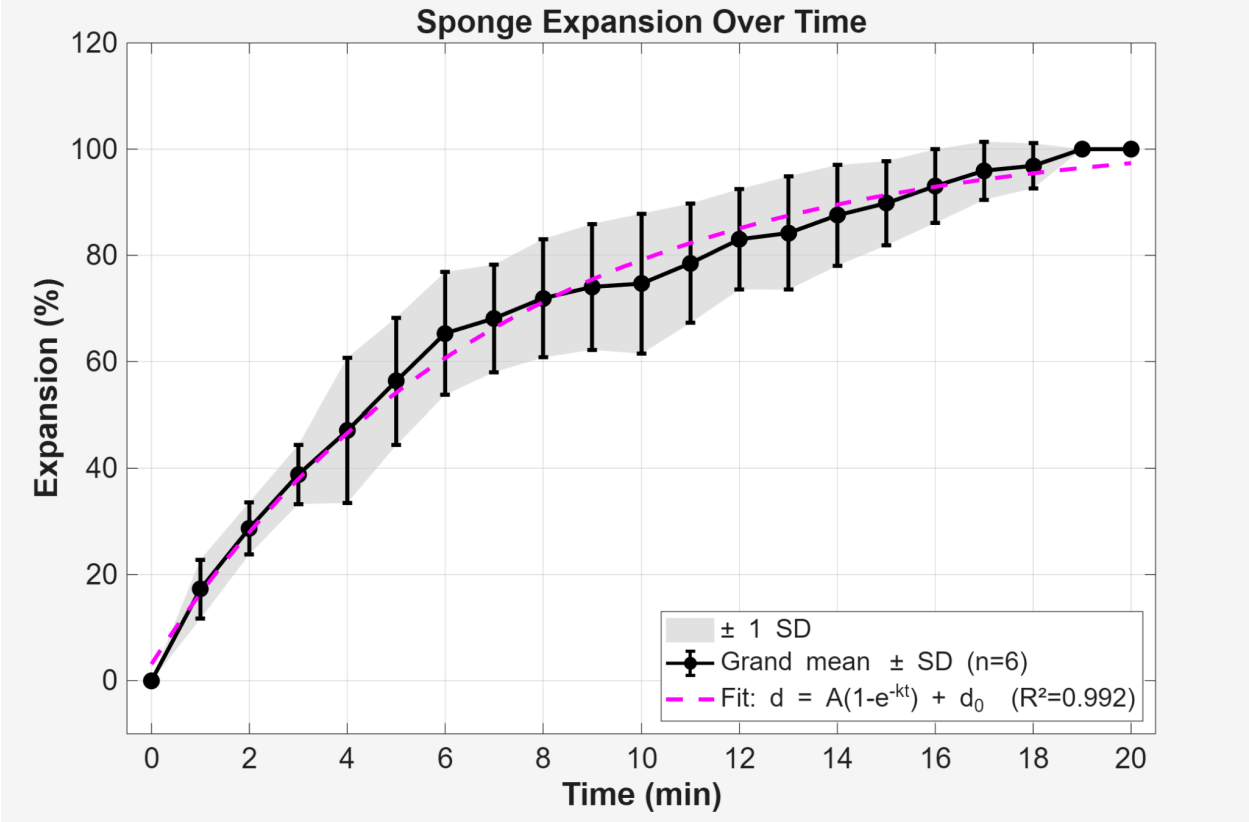

Figure 12: Mean gelatin coated sponge expansion in PBS

Gelatin coated sponges demonstrated consistent and near-complete re-expansion under simulated physiological conditions. The grand mean expansion across all six replicates followed an asymptotic trajectory, well described by an exponential saturation model of the form $d = A(1 - e^{-kt}) + d_0$, with a rate constant of $k = 0.1428$ per min, and an R^2 of 0.992, indicating that the model accounts for 99.2% of the variance in the expansion data. The high goodness of fit confirms that re-expansion proceeded in a predictable, repeatable manner across replicates. Mean expansion reached approximately 75% within the first 10 minutes and approached full recovery by 18 to 20 minutes, at which point all sponges had returned to their original diameter. Moderate inter-replicate variability was observed in the early expansion phase, reflected in the standard deviation band, and is consistent with the qualitative observation that gelatin adhered unevenly to the back surface of some sponges, producing asymmetric initial expansion. Variability narrowed substantially by 18 to 20 minutes as all sponges converged on full expansion. However, while full re-expansion was achieved, expansion was confirmed to begin well within the 15 minute deployment window required for safe endoscopic placement, meaning the coating cannot be relied upon to maintain sponge compression for a sufficient duration prior to expansion. Future work will therefore investigate sodium alginate in both crosslinked and uncrosslinked formulations as an alternative coating material, with the aim of achieving greater control over dissolution rate and identifying a formulation that reliably maintains structural integrity

throughout the full deployment window before permitting sponge re-expansion. See Appendix XI for MATLAB code.

Discussion

Analysis of gelatin and sodium alginate revealed that sponge encapsulation with a biodegradable material is a potential solution to improve EndoVAC deployment. Currently, sodium alginate appears to be the best material for long term development. The swelling and degradation properties of the gelatin and gelatin film may prevent future development as a viable material. The rapid swelling of the gelatin film when exposed to physiological conditions may result in more force needed to deliver the EndoVAC sponge, therefore increasing the difficulty of the procedure.

Additionally, the gelatin film was able to encapsulate the sponge and prevent sponge expansion. This design proves that a biomaterial can compress a sponge and improve EndoVAC deployment efficiency. However, the final design remained stable until exposed to physiological conditions, where quick degradation and sponge expansion was observed. This expansion was likely due to gelatin's low melting point around 32°C and a lack of crosslinking between polymer chains. While sponge expansion was tested, various forms of error may have been attributed to uneven sponge expansion and decreased diameter measurement accuracy. Optical measurements through water may have introduced refraction error, affecting diameter accuracy. Future testing of sponge expansion will account for refractive error to gather accurate diameter measurements as the sponge expands. Due to a lack of an available incubator, a hot plate was used to heat the samples to 37°C. At room temperature, setting the hot plate to 37°C would not maintain physiological conditions. This resulted in the hot plates being set to 45°C, and a temperature probe was used to ensure the solution temperature remained at 37 ± 1°C. Variable temperature between sample groups, as well as temperature fluctuations during testing may have contributed to faster sponge expansion. An incubator will be used for further testing to minimize the error based upon temperature differences.

While the use of gelatin allowed for sponge encapsulation, ethical concerns about porcine derived gelatin may exclude further gelatin use. By continuing to pursue porcine derived gelatin as a solution, patient access to the device will be limited. Sodium alginate, a cost effective polymer derived from brown algae, is a promising alternative. Further fabrication and development of sodium alginate is needed to complete sponge encapsulation.

Initial degradation testing of crosslinked sodium alginate reveals that the polymer will remain stable and not lose mass within the first 15 minutes of exposure to physiological conditions. However, the precision between tested samples of sodium alginate was inconsistent. A potential source of error was the method of crosslinking. Due to the sodium alginate samples remaining a viscous liquid and not solidifying, 0.8 M $CaCl_2$ was applied to the surface of each sample. This method of exposing divalent cations may have resulted in a higher crosslinking density on the surface of each sample. As a result of inconsistent calcium ion exposure, each sample experienced variable crosslinking and could have resulted in less precise measurements

between groups. A change to this testing would be to allow the samples to further dehydrate and form a solid hydrogel. This would allow each sample to be dipped in a $CaCl_2$ solution and experience consistent crosslinking from calcium ions.

In terms of the design of the biodegradable coating, the team would like to expand on the fabrication of a sponge encapsulated in sodium alginate. Preliminary fabrication with the mold used for the gelatin film was unable to produce a sponge encapsulated in sodium alginate. Development of a new mold or encapsulation technique will be needed.

Conclusion

Endoluminal vacuum therapy has demonstrated strong clinical success in treating anastomotic leaks, but its widespread application is limited by the labor and endoscopic skill required from the surgeon. To address these issues, a sponge was compressed and a degradable coating was applied. The coating stays intact for 15 minutes during placement, and will degrade once in the cavity, allowing expansion to original size. A gelatin hydrogel, gelatin film, and crosslinked sodium alginate were evaluated as coating candidates. During degradation testing, gelatin hydrogel dissolved too quickly, but the gelatin film and crosslinked sodium alginate outlasted the 15 minute requirement. Sponge expansion testing with gelatin film yielded an exponential growth curve with full expansion within 20 minutes. Sodium alginate did not undergo sponge expansion testing because preliminary fabrication with the mold was unsuccessful. While the gelatin film meets requirements, further testing with sodium alginate is required for comparison. To achieve this, fabrication protocols for putting the sodium alginate on the sponge and the coating itself will have to be standardized. Additionally, the time of degradation will need to be tuned to 15 minutes by experimenting with different crosslinking and drying methods. After a final material has been validated, testing in an esophageal model will be done to better simulate surgical conditions.

For this device to be utilized in operating rooms, rigorous FDA and hospital approval protocols must be completed. After a successful encapsulated sponge method is developed, biocompatibility testing must be thoroughly investigated to prevent potential inflammation upon delivery [19]. The device would classify as a Class II medical device under the classification on endoscopes and accessories. However, the process for FDA approval would be relatively simple as the biodegradable coating would qualify as an endoscopic sponge carrier and would be exempt from premarket notification procedures [20]. Approval on the use of the device would be individualized by hospitals, however, proof of an easier deployment method would streamline the process of getting the device into hospitals around the world.

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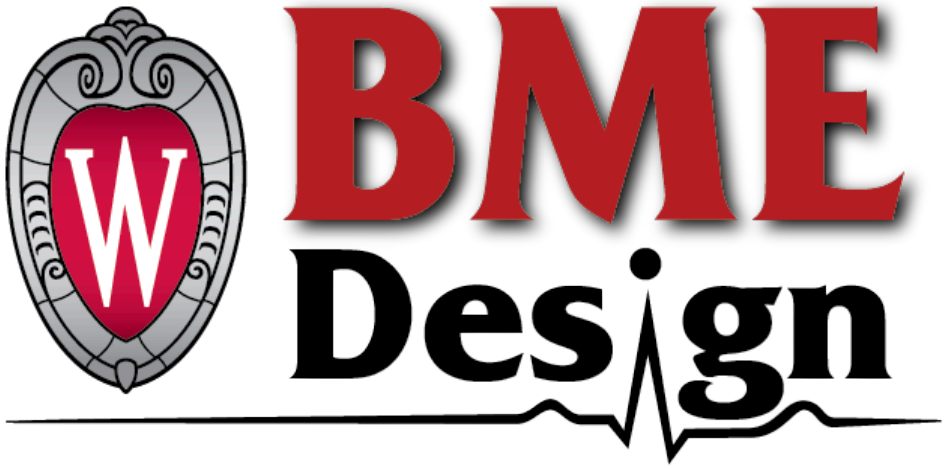
Appendices

1.19. Appendix I: Product Design Specification



Democratizing Placement of Endoluminal Negative Pressure Devices for Gastrointestinal Leaks

Preliminary Product Design Specifications

BME 301 Lab 301

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Client: Dr. Amber Shada

Advisor: Prof. John Puccinelli

February 5, 2026

Function:

Traditionally, large defects in the gastrointestinal (GI) tract are treated with surgery. Recently, some surgeons have had success utilizing negative pressure therapy, which is used to improve healing of superficial wounds. The placement of the device in the GI tract is currently very labor intensive and requires skillful manipulation of an endoscope. Development of a streamlined procedure to deploy negative vacuum therapy in the GI tract would make the therapy accessible to more surgeons.

Client requirements:

- The client requires an endoscopic vacuum therapy device capable of delivering a sponge to a cavity within the gastrointestinal tract.
- The client requires the device to be used to treat gastrointestinal leaks with a minimum cavity size of 2cm.
- The client requires the device to be deployable in conjunction with the use of current clinical endoscopes.
- The client prefers the design to be compatible with V.A.C Grandufoam Dressings, enabling integration with existing clinical materials.
- The client intends the device to be suitable for use in both the upper and lower gastrointestinal tracts.
- The client intends the device to have single patient use to reduce the risk of cross-contamination and infection.
- The client requires the device to be suitable for use with patients under anesthesia.

Design requirements:

1. **Physical and Operational Characteristics**
    a. *Performance requirements*
        i. The device must retain the same properties as current EndoVAC therapy. This includes macro and microdeformation of tissue, increased perfusion, fluid removal, and bacterial clearance [1].
        ii. Allow intracavity or intraluminal placement of the sponge [1].

b. *Safety*
    i. The combined diameter of components utilized simultaneously must be smaller than 2-3cm in diameter to prevent trauma to the upper esophageal sphincter [1].
    ii. The design must consider proper fixation of the nasogastric tube to prevent continuous compression of the nasal wall, which leads to nasal wing necrosis and nose deformation [2].
    iii. Formation and rupture of a pseudoaneurysm within the aorta and its branches is a risk during vacuum therapy in the upper gastrointestinal tract [2].
    iv. Increased time of contact between the tissue and absorbent material increases ingrowth that can cause minor bleeding when removed [3].
c. *Accuracy and Reliability*
    i. The device must retain or improve upon the current success rate of 90%.
d. *Life in Service*
    i. The device must be replaced every 3-7 days [3].
    ii. The device has to stand up to pressures used in current EndoVAC therapy, 125mmHg - 175mmHg [1].
e. *Shelf Life*
    i. The device shall be able to remain within sterile packaging for up to 3 years without losing functionality
f. *Operating Environment*
    i. Internal components (in situ with GI tract)
        1. Temperature will be approximately body temperature (36-38°C) for the duration of therapy.
        2. 100% relative humidity should be assumed as the device will be fully saturated with bodily fluids including gastric secretions, bile, pancreatic enzymes, intestinal contents, and blood.
        3. Chemical exposure will differ depending on the region of the GI tract.
            a. Upper GI: gastric acid (pH 1.5-3.5).
            b. Lower GI: intestinal contents (pH 5.5-8), includes digestive enzymes, pepsin, bile salts, pancreatic enzymes, fecal matter.
        4. There will be continuous negative pressure applied to the sponge per clinical protocol.

5. Mechanical force such peristaltic movements and patient motion should be considered
6. Within a biological environment: in contact with mucosal tissue, exposure to endogenous bacteria and potential pathogens.

g. Ergonomics

i. Implantation of the device shall be less than 2 hours to reduce strain on the surgeon and reduce the risk of procedure-related complications.

ii. During implantation, the product must remain stable to ensure safe and effective placement within the gastrointestinal tract.

iii. The device shall be capable of being installed by a single surgeon without the application of excessive force.

iv. The device should be able to be implanted by a first time user without extensive prior training as to reduce the likelihood of user error

1. An external instruction manual shall be used as the product is a Class II medical device [4].

h. Size

i. The outer diameter of both the vacuum/drainage catheter and foam sponge together must be small enough to pass atraumatically through the esophagus or colon alongside or through an endoscope (typically around 2cm), while maintaining sufficient size for effective drainage and structural integrity.

ii. The foam sponge alone:

1. Should accommodate GI leaks with defect sizes of 2-15 cm; defects larger than 15-18 cm may not be suitable for sponge-based therapy due to anatomical constraints of the GI tract.
2. Must compress to a low profile for ease of deployment through GI tract.
3. Must be able to expand sufficiently upon deployment into the cavity to conform to and fill the irregular space.

i. Weight

i. Lightweight to prevent device migration due to gravity, peristalsis, or patient movement. Device must remain securely positioned within the cavity throughout the treatment period without causing pressure-related tissue injury.

j. Materials

i. All materials must be biocompatible per ISO 10993 standards for devices in prolonged contact with mucosal tissue (>24 hours) [5]

ii. Material must maintain structural integrity throughout treatment duration (typically 3-7 days) and be removable intact via endoscopy. [3]

iii. Materials must not elicit inflammatory or immune responses in the GI tract

iv. The material must have an open-pore structure to allow fluid permeability which enables effective drainage of fluids and secretions under negative pressure.

v. Material must be able to conform to irregular defect geometries and tolerate GI peristalsis without tissue trauma.

vi. Must withstand exposure to gastric acid (pH 1.5-3.5), bile, pancreatic enzymes, and other GI secretions without degradation.

vii. Current materials used for sponge include:

1. Polyurethane (PU) open-pore sponges: most commonly used material in endoVAC applications due to its favorable drainage properties and flexibility. KCL black polyurethane foam, originally designed for external wound VAC therapy, is frequently adapted for endoluminal use. Other medical grade PU foams with varying pore sizes and densities are used in prototype and commercial devices such as the Eso-SPONGE. [6] [7]

k. Aesthetics, Appearance, and Finish

i. Foam Portion Appearance:

1. Conformability: foam must be soft and pliable to bend and conform to anatomical curves and irregular leak cavities without causing mucosal trauma.
2. Texture: Open-pore reticulated structure with interconnected pores to enable effective cavity geometries.
3. Shape: Cylindrical with tapered end to facilitate insertion and positioning within irregular cavity defects.
4. Surface finish: smooth, non-abrasive outer surface to minimize friction and tissue injury during deployment through the esophagus or colon.

ii. Vacuum/drainage catheter

1. Flexibility and torqueability: Catheter must have sufficient column strength and torque transmission to allow controlled positioning and deployment into the defect cavity, while remaining flexible enough to navigate anatomical curves (esophagus, stomach, colon)
2. Surface finish: Smooth outer coating to facilitate easy passage through GI tract.
3. Length: Adequate length to reach target locations in upper GI (esophagus, stomach, duodenum) and lower GI (colon, rectum) tracts.

iii. Overall Design:

1. Compactness: Device should compress sufficiently for passage through the GI tract and then expand within the cavity to fill defect space.
2. Deployment and handling: Design should minimize technical difficulty during cavity deployment through smooth surfaces and compatibility to be manipulated with forceps for precise positioning. All edges, connections, and surfaces must be smooth and rounded to prevent tissue trauma.

2. Production Characteristics

a. Quantity

i. The device is designed for single-patient use in endoluminal negative pressure therapy. Clinically, endoluminal vacuum therapy (EVT) requires foam exchange approximately every 7 days due to secretion accumulation, decreased suction efficiency, and tissue ingrowth. Reported clinical data indicate an average EVT duration of 35.8 days, with a mean of 7.2 foam exchanges per patient [2]. Based on these findings, this project aims to develop a system capable of supporting up to 30 foam exchanges per patient, while utilizing a single functional deployment device.

b. Target Product Cost

i. The initial budget for the project is $500 to $1,000, and this will be the target cost per unit.

ii. The client will provide current equipment used to construct VACs (foam, nasogastric tube, suture) and endoscopy if needed.

3. **Miscellaneous**

a. Standards and Specifications

i. Endoscopes and accessories are classified as Class II medical devices since the equipment can pose moderate risk to patients during operation [4].

1. EndoVAC devices, including sponges, are Class II (special control) devices subject to premarket notification 501(k). If the proposed device is not substantially equivalent to a predicate device, clinical trials are required for premarket approval [8].

ii. The International Organization for Standardization (ISO) has multiple standards that apply to the development of endoscopic devices for use within the gastrointestinal tract.

1. ISO 10993 defines requirements for biomaterials if they come in contact with the body [5].
    a. ISO 10993-1 section 6.4.4.4 requires biological effects to be evaluated for medical devices in contact with intact mucosal membrane [5].
    b. ISO 10993-1 section 6.4.4.4 requires biological effects to be evaluated for medical devices in contact with breached or compromised surfaces or internal tissue other than circulating blood [5].
2. ISO 8600 defines the requirements for endoscopes and endotherapy devices used in the practice of medicine [9].
    a. ISO 8600-4 requires that the maximum width of the insertion portion must be determined to ensure compatibility with human anatomy and other devices [9].
3. ISO 14971 requires the application of risk management to estimate the probability of occurrence of harm and the consequences of such harm [9].

b. Customer

i. The primary customer is the endoscopic and laparoscopic gastrointestinal surgeon at UW Hospital, represented by the client, Amber L. Shada. The device must support a simplified EVT deployment system that reduces procedural complexity and enables wider clinical use.

ii. Patients receiving EVT include individuals with upper or lower gastrointestinal transmural defects, most commonly postoperative anastomotic leaks following esophageal, gastric, or colorectal surgery, with this project focusing primarily on upper GI tract patients [1].

iii. This population also includes patients with infected cavities or abscesses who are already receiving antibiotic therapy.

c. Patient-related concerns

i. Nasogastric tubes cause patient discomfort, especially for those also using a nasoenteric tube [1].

ii. Multiple procedures to exchange the sponge causes patient distress [1].

iii. Although there is not a well known cause, treatment of anastomotic leaks can lead to esophageal and stomach strictures. Strictures require an additional procedure, dilation, to treat [2].

d. Competition

i. The Endo-SPONGE® and Eso-SPONGE®, developed by B. Braun Melsungen, are minimally invasive methods for treatment of anastomotic leakage [10]. The Endo-SPONGE® is used in the low pelvic area while the Eso-SPONGE® is used in the upper gastrointestinal tract. The method utilizes an endoscope, an overtube, and a polyurethane sponge. The overtube and endoscope are used to place the sponge in the gastrointestinal defect. Controlled continuous negative pressure of 100-125 mmHg is applied via a transnasal gastric tube using an electronic vacuum pump. The system comes prepackaged and is available for purchase from Boston Scientific.

ii. The Suprasorb® CNP is an open-pore film drainage system that has been adapted for treatments of anastomotic leaks [11]. The system includes a perforated film that is attached to a 16F gastric decompression tube using a suture. This film drainage system is then passed to the desired treatment location using the guidance of an 8F feeding tube. Once the film is in place, negative pressure is applied to treat small defects. This treatment option offers reduced adhesiveness of the film compared to a sponge, easy removal, and decreased damage to surrounding tissue.

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1.20. Appendix II: Design Matrix

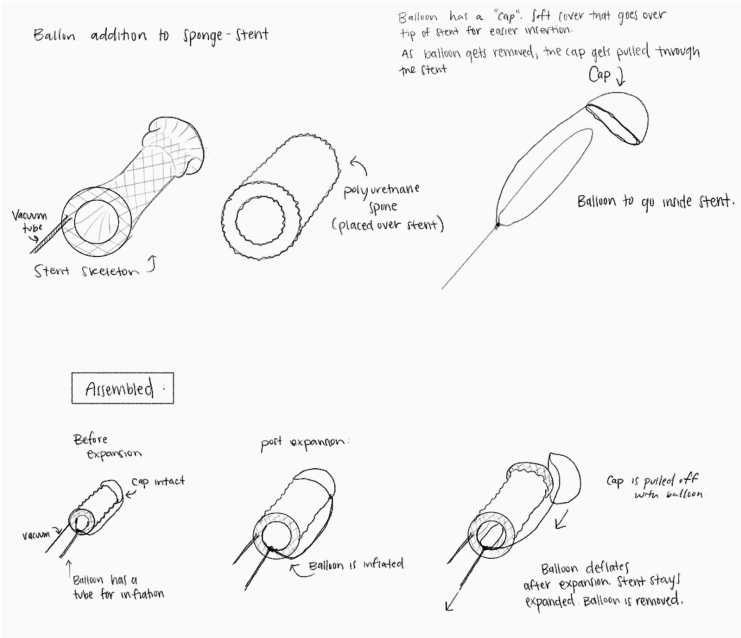

Figure 1. Balloon Sponge-Stent

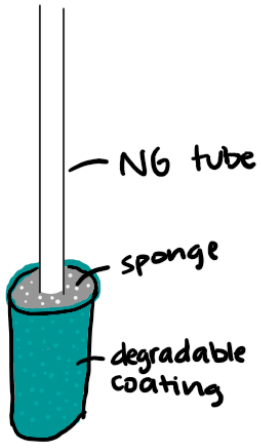

Figure 2. Degradable Coating Design

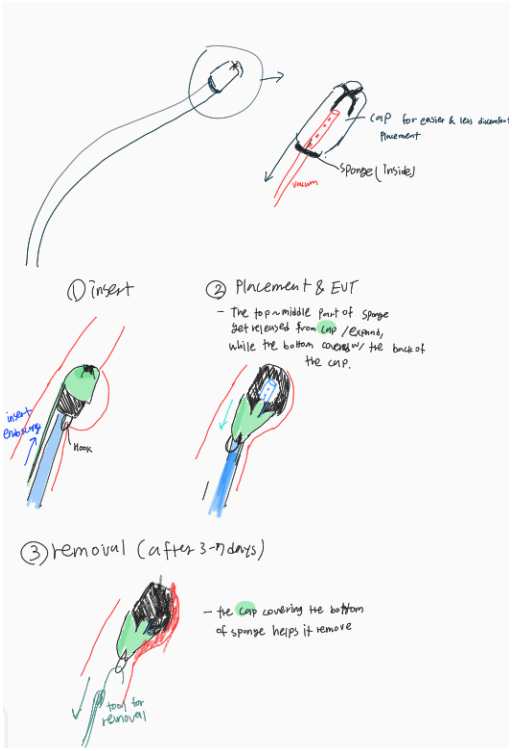

Figure 3. Cap Delivery Design

Criteria	Weight	Balloon Stent		Degradable Coating		Cap Delivery	
Safety	**17.5**	3/5	10.5	**4/5**	**14**	3/5	10.5
Ease of Placement	**17.5**	3/5	10.5	**4/5**	**14**	3/5	10.5
Ease of Removal	**15**	2/5	6	**4/5**	**12**	3/5	9
Ease of Fabrication	**15**	2/5	6	3/5	9	**4/5**	**12**
Patient Comfort	**15**	**4/5**	**12**	3/5	9	2/5	6
Adjustability	**10**	2/5	4	**4/5**	**8**	3/5	6
Cost	**10**	2/5	4	3/5	6	**4/5**	**8**
Total (100)	**100**	53/100		**72/100**		**62/100**	

Criteria Descriptions:

Safety (17.5%): This category takes into consideration risks that occur during surgery, placement, duration of use, and removal. Because this device is being placed into the patient's esophagus endoscopically, the device must comply with ISO 8066-4 to ensure anatomic and endoscopic compatibility [1]. Additionally, all materials must be biocompatible as stated in ISO 10993:1 [2]. This criteria has a high weight because it is necessary to ensure that the device will not cause harm to the patient.

Ease of Placement (17.5%):
This criteria evaluates how efficiently and reliably each design can be delivered to the target site within the gastrointestinal tract. Factors considered include the number of steps and overall complexity of the insertion procedure, the level of technical skill required from the operating surgeon, and the estimated time to complete placement (ideally under 5 second placement time).

Ease of Removal (15%):
This criteria evaluates how safely and simply each design can be retrieved from the gastrointestinal tract, either for sponge exchange or at the conclusion of treatment. Factors considered include how easily the device can be detached and retrieved endoscopically, and the risk of mucosal trauma or tissue damage during withdrawal.

Ease of Fabrication (15%): This criteria addresses the ability to produce and assemble all components of the design. The design must be prototyped and completed within the given time frame, so designs with higher scores better align with the fabrication skills of the team. The weight of this criteria reflects the importance of prioritizing client and patient needs while recognizing feasibility.

Patient Comfort (15%): Patient comfort directly influences postoperative satisfaction and overall treatment outcomes. Because EVT requires prolonged intraluminal placement and repeated sponge exchanges, patients may experience foreign body sensation, pain, dysphagia, and chest discomfort, which can lead to reduced compliance or premature termination of therapy [4]. Mechanical irritation from the device may also trigger gag reflex or aspiration risk, affecting procedural safety. Therefore, our device design must prioritize patient comfort not only during long-term placement but also during insertion and removal, ensuring a low-profile, flexible structure that minimizes tissue irritation and procedural burden.

Adjustability (10%): Adjustability of the device allows it to fit various size cavities depending on the patient's needs. This is an important design consideration because the gastrointestinal tract exhibits significant anatomical variability both between patients and within different regions of the same patient's GI system. The esophagus, stomach, small intestine, and

colon each have distinctly different diameters, with the esophagus ranging from 2-3 cm, the stomach expanding to 10-15 cm, and the colon measuring 5-8 cm in diameter [3]. Additionally, pathological conditions such as perforations, fistulas, or surgical defects create cavities of unpredictable sizes and geometries.

Cost (10%): Cost should be minimized to decrease the cost of fabrication and therefore the cost of the procedure. Repeat procedures can drive up the cost of treatment for the patient. The cost of the design will be determined by the materials used for fabrication. This criteria ranks sixth in the design matrix and should be considered for all designs.

Ranking Analysis:

Balloon Sponge-Stent:

This design received 3/5 for safety. The stent provides excellent structural stability and creates a secure seal from the cavity, which is a significant advantage. However, the multiple components increase potential failure points such as balloon rupture or stent displacement, and the overall complexity may increase risk of procedural complications.

The balloon stent design scored 3/5 for ease of placement. The cap attachment does help guide the device through the esophagus and reduces friction during navigation, which simplifies insertion to some degree. However, the overall procedural workflow is more complex than the other designs due to the number of components involved

This design scored 2/5 for ease of removal. While the stent provides structural stability during use, that same rigidity makes retrieval more involved. Detaching and collapsing the stent for withdrawal requires additional endoscopic steps, and the multiple components increase the likelihood that part of the device could snag or resist during removal.

This design received 2/5 due to manufacturing complexity. The device requires integration of multiple complex components including the stent, balloon inflation mechanism, PU sponge, and cap. Each component requires quality control testing, and the assembly process adds significant engineering challenges and production time.

The balloon stent scored highest in this category at 4/5. The stent seal allows the patient to eat and drink normally throughout treatment, significantly improving quality of life. The structural stability also provides patients with a better sense of security, though the multiple components may create more bulk or physical sensation.

The balloon stent scored low at 2/5 for adjustability. Once the stent is deployed and the balloon is inflated, repositioning becomes very difficult. There is limited ability to adjust the size of this device due to its many components.

This design scored 2/5 for cost-effectiveness. The multiple specialized components, particularly the medical-grade stent and inflation balloon mechanism, are expensive to manufacture. Complex assembly processes and stringent quality control requirements further increase production costs.

Degradable Coating Design:

This design received 4/5 for safety considerations. The fewer mechanical components reduce potential failure modes compared to the balloon stent design. However, the lack of structural support from a stent raises concerns about maintaining stable positioning, and unpredictable gelatin degradation timing could lead to premature sponge expansion and complications.

The degradable cover design scored 4/5 for ease of placement. The absence of a stent or balloon means the surgeon works with fewer components and has a simpler, more streamlined insertion process. The compressed sponge within its coating maintains a low profile that navigates the esophagus with minimal resistance. However, the degradation timeline of the gelatin creates a narrow window for correct positioning.

This design scored 4/5 for ease of removal. Because there is no rigid stent or mechanical anchoring system, the sponge can be retrieved with relatively straightforward endoscopic grasping.The main concern is ensuring the sponge has not adhered to surrounding tissue during the treatment interval, which introduces minor retrieval variability.

This design received 3/5 for fabrication ease. Fewer total components simplify the overall manufacturing process compared to the other designs. However, precise formulation of the degradable gelatin film is critical to achieve reliable and consistent degradation timing. The attachment mechanism between the film, sponge, and VAC catheter still requires careful engineering and testing.

The degradable cover scored 2/5 in patient comfort. Without a stent to provide structural support, patients likely cannot eat safely due to the risk of dislodging the sponge with food or drink. This creates significant lifestyle restrictions during the treatment period, though the simpler profile may be less physically noticeable.

The degradable cover scored well at 4/5 for adjustability. This design allows for easy selection of different sponge sizes to accommodate varying cavity dimensions, providing flexibility to match patient-specific anatomy. The compressed sponge format makes it simple to stock and choose from multiple size options during the procedure.

This design scored 3/5 for cost-effectiveness. The fewer components and use of relatively inexpensive materials like PU sponge and gelatin film reduce overall production costs. The simpler manufacturing process and standard VAC catheter component make this a more economical option than the balloon stent design.

Cap Delivery Design:

This design received 3/5 for safety. The biocompatible plastic cap provides protection during insertion shielding the esophagus from contact. Due to the fact the cap will remain in the esophagus until replacement. Also, the protective cap structure reduces mucosal trauma during deployment and removal. However, as it remains in the body for extended periods, there are concerns regarding foreign body effects.

The cap delivery design scored 3/5 for ease of placement. The sponge can be preloaded and compressed into the cap ahead of time, which simplifies intraoperative preparation. Once inserted, the cap guides the sponge along the anatomical pathway and reduces direct contact between the sponge and esophageal mucosa during delivery.

This design scored 3/5 for ease of removal. The cap provides a defined structure that can be grasped and retracted endoscopically in a relatively controlled manner, which reduces some of the unpredictability seen with uncoated sponge retrieval. However, there is a risk of the cap becoming detached and migrating distally through the GI tract during the treatment period, complicating or preventing straightforward retrieval.

This design received 4/5 (12 points) for ease of fabrication. The main component is a biocompatible plastic cap, which can be produced via 3D printing or injection molding using medical-grade polymers. Assembly is relatively simple, as the sponge only needs to be compressed and inserted into the cap. Compared to multi-component systems, this design minimizes mechanical integration challenges.

The cap delivery design scored 2/5 for patient comfort. Because the plastic cap remains inside of the esophagus during treatment, patients may experience foreign body sensation, gag reflex, or discomfort during swallowing. These factors may reduce overall comfort during prolonged therapy.

The cap delivery system scored 3/5 (12 points) for adjustability. Different sponge sizes can be compressed and inserted into the plastic cap, allowing compatibility with various cavity dimensions. However, the maximum size of the sponge is still constrained by the internal diameter of the cap, limiting its ability to address larger defects. Also, considering the thickness of the cap, the overall thickness must remain small enough to pass safely through the esophagus. Because of the physical constraints, the adjustability is moderate.

This design scored 4/5 (8 points) for cost-effectiveness. Medical-grade biocompatible plastics are relatively inexpensive to manufacture compared to metal stents or balloon systems. Manufacturing costs would mainly come from material validation and quality control processes rather than raw material expenses. The relatively simple structure helps keep the cost manageable

Works Cited

[1] "ISO 10993-1:2025," ISO. Accessed: Feb. 03, 2026. [Online]. Available: https://www.iso.org/standard/10993-1

[2] "ISO 10993-1:2025," ISO. Accessed: Feb. 03, 2026. [Online]. Available: https://www.iso.org/standard/10993-1

[3] H. F. Helander and L. Fändriks, "Surface area of the digestive tract – revisited," Scandinavian Journal of Gastroenterology, vol. 49, no. 6, pp. 681–689, Jun. 2014, doi: 10.3109/00365521.2014.898326.

[4] O. Möschler, C. Nies, and M. Mueller, “Endoscopic Vacuum Therapy for Esophageal Perforations and Leakages,” Endoscopy International Open, vol. 03, no. 06, pp. E554–E558, Aug. 2015, doi: https://doi.org/10.1055/s-0034-1392568.

1.21. Appendix III: Technical Drawing of Mold

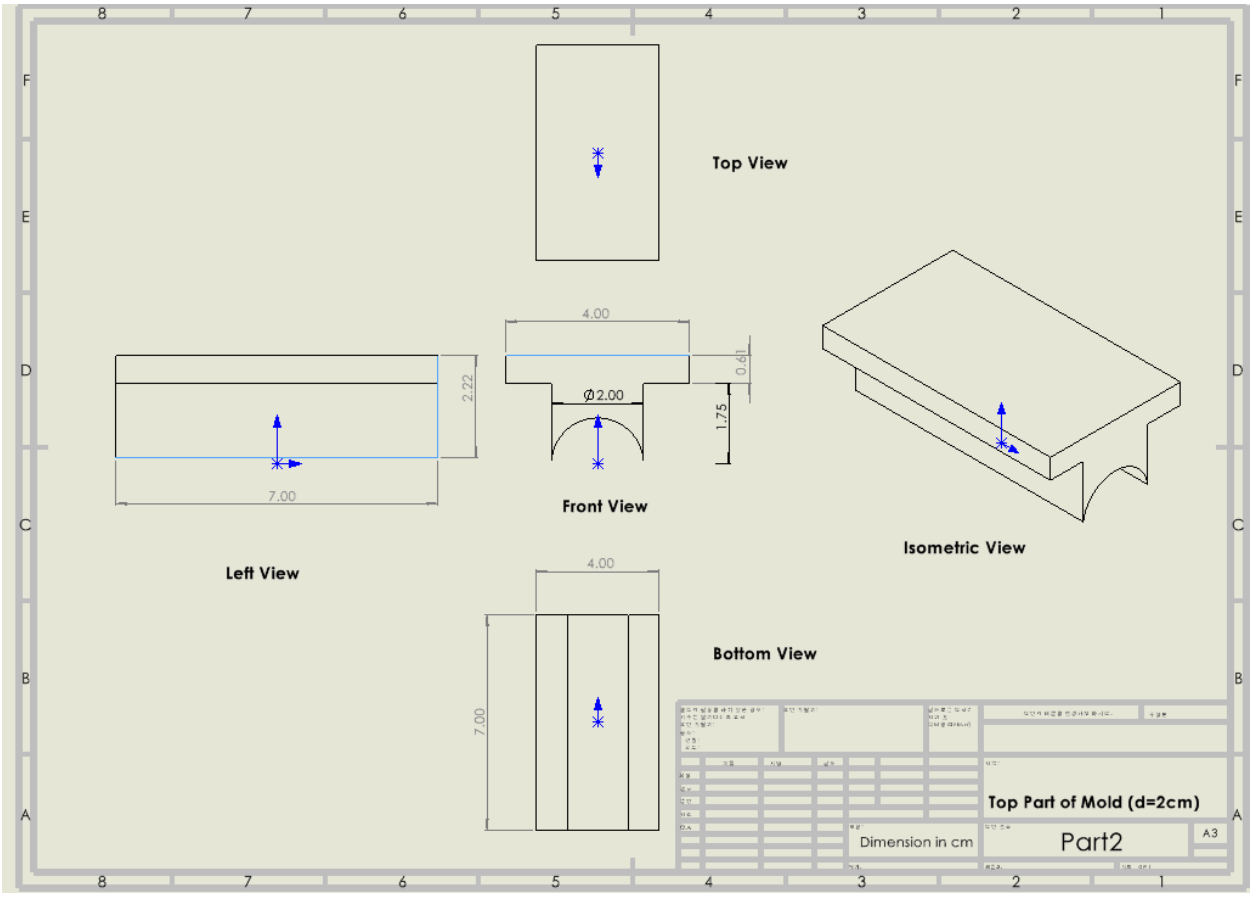

Figure 1. Solidworks Technical Drawing of Top Mold

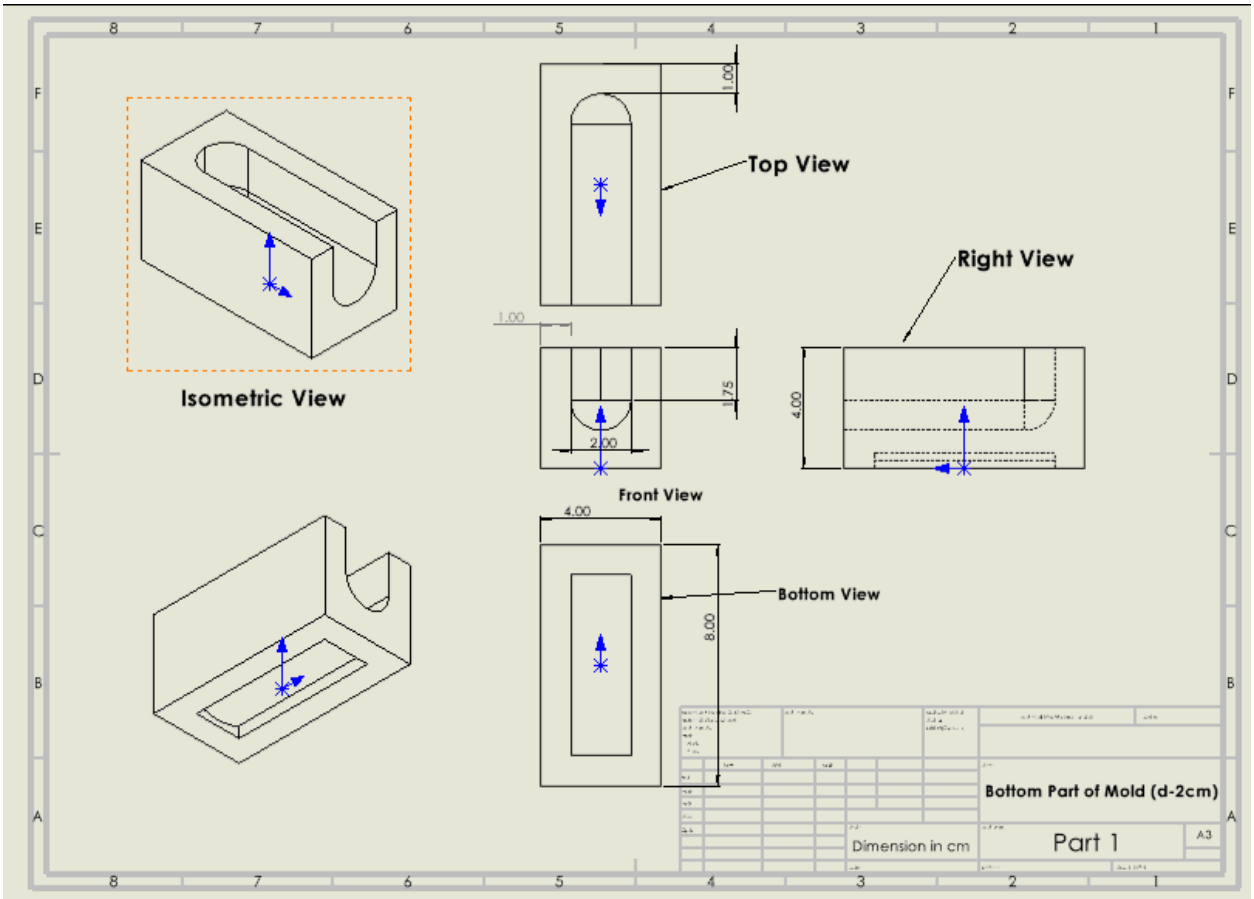

Figure 2. Solidworks Technical Drawing of Bottom Mold

1.22. Appendix IV: Expense Spreadsheet

Item	Description	Manufacturer	Mft Pt#	Vendor	Vendor Cat#	Date	QTY	Total	Link
Category 1									
Sodium Alginate	Alginic acid sodium salt from brown algae, Algin, Sodium alginate	Sigma Aldrich	W201502	Sigma Aldrich	W201502	500g	1	$0.00	Link
Calcium Chloride Dihydrate	147.02 g/mol	Fisher Scientific	BO510-510	Fisher Scientific	C79-500	500g	1	$0.00	Link
Porcine Gelatin	CAS 9000-70-8 Type A	Sigma Aldrich	G1890	Sigma Aldrich	9000-70-8	300g	1	$0.00	Link
Glycerol	Density 1.261 g/mL	Fisher Scientific	G314	Fisher Scientific	G314	4L	1	$0.00	Link
Category 2									
3D Print 1	PETG mold	-	-	-	-	-	5	$8.15	
3D Print 2	TPU mold	-	-	-	-	-	1	$3.28	
							Total	**$11.43**	

1.23. Appendix V: Gelatin Fabrication Protocol

8:1 Gelatin Sheet Fabrication Protocol

Materials:

- Safety equipment:
  - Gloves
  - Fume hood
- Measuring equipment
  - Fisher Science Education Portable Balance, Model: SLF303
  - Fisherbrand small weigh boat
  - Scoopula
  - 1mL serological pipette: Falcon 357525
  - 25mL serological pipette: Falcon 357525
- Gelatin-glycerin material
  - Porcine Gelatin: Sigma-Aldrich
    - Type A, CAS 9000-70-8, 70-90% protein, MW 50-100 kDa, powder form
    - 2.5g needed
  - Glycerin: Fisher Scientific G314
    - Density 1.261g/mL
    - 0.4mL needed
  - Deionized water
    - 50mL needed
  - 100mL beaker used to mix gelatin solution
  - Fisherbrand Isotemp Digital Hotplate Stirrer
  - Magnetic stir bar
  - 25cm x 25cm Corning bioassay dish

1. Setup fume hood for use
   a. See instructions on the fume hood for proper setup
2. Prepare gelatin powder
   a. Zero a small weigh boat using scale
   b. Measure 16 g of 300 g bloom porcine gelatin in the weigh boat using a scoopula
   c. Transfer gelatin powder to 400 mL beaker
3. Place 100 mL beaker with gelatin powder on a hot plate in a fume hood
4. Using a 25 mL serological pipette, add 128 mL of deionized water to the beaker
5. Place beaker on digital hotplate stirrer
   a. Set magnetic stir to a medium-low speed (~400 rpm)
   b. After water and gelatin are combined, set temperature to 50°C
6. Add glycerin to beaker at a ratio of 20% weight relative to the mass of gelatin used

    a. For this application, use 2.54mL of glycerin
    b. Measure 2.54mL of glycerin and add to beaker using 1 mL serological pipette
7. Allow gelatin-glycerin solution to mix for 30 minutes at 50°C to ensure homogenous solution
8. Transfer all of mixed solution to 25cm x 25cm Corning bioassay dish
9. Allow solution to solidify, covered at room temperature for 12 hours

1.24. Appendix VI: Sodium Alginate Fabrication Protocol

Crosslinked Sodium Alginate Fabrication Protocol

Materials:

- Safety equipment:
  - Gloves
  - Fume hood
- Measuring equipment:
  - Fisher Science Education Portable Balance, Model: SLF303
  - Fisherbrand small weigh boat
  - Scoopula
  - 10mL serological pipette: Falcon 357525
  - 1mL serological pipette: Falcon 357525
- Sodium alginate material:
  - Keltone LVCR: FMC Biopolymer
  - Deionized water
  - 100 mL beaker
  - 100 mm x 20 mm pyrex petri dish
- 0.8M crosslinking solution
  - Calcium Chloride Dihydrate: Fisher Scientific C70500
    - 147.02 g/mol, Manufacturer: Fisher Scientific BO510-510
  - Deionized water
  - 1000mL beaker
- Magnetic stir bar
- Fisherbrand Isotemp Digital Hotplate Stirrer

Procedure:

1. Setup fume hood for use
   a. See instructions on the fume hood for proper setup
2. Prepare dissolved sodium alginate solution
   a. Using a serological pipette, add 80mL of distilled water to 100mL beaker
   b. Place beaker with water onto a hot plate in fume hood set to 60 ± 0.5 °C and heat water for 10 minutes
   c. Zero a weigh boat using scale
   d. Measure 1.6g (2% w/v) Keltone LVCR in weigh boat using scoopula [1]
   e. Transfer sodium alginate powder to 100mL beaker and add magnetic stir bar
   f. Pour warmed water into 100mL beaker containing powder
   g. Place beaker on hot plate in fume hood and set magnetic stir to medium-low speed (~400 rpm)

h. Add 0.634mL of glycerin into beaker with sodium alginate solution
i. Leave to stir for 1 hour
j. Pour mixture into petri dish
k. Place petri dish with mixture in a drying oven set to 60 ± 0.5 °C for 12 hours

3. Prepare 0.8M calcium chloride crosslinking solution
    a. Zero a small weigh boat using scale
    b. Measure 11.76g of calcium chloride into the weigh boat using a scoopula
    c. Transfer calcium chloride to a 400mL beaker
    d. Place 400mL beaker with calcium chloride powder on a hot plate in a fume hood
    e. Using a serological pipette, add 100mL of distilled water to 400mL beaker
    f. Place magnetic stir into the 1000mL beaker and turn on hot plate:
        i. Set hot plate to 24 ± 0.5 °C
        ii. Set magnetic stir to a medium-low speed (~400 rpm)
        iii. Leave to stir for 15 minutes
4. Immerse sodium alginate film in calcium chloride solution
    a. Remove sodium alginate from oven and remove gel from petri dish
    b. Submerge sodium alginate film in calcium chloride bath for 2 minutes
    c. Place back on petri dish

References

[1] A. Cano-Vicent *et al.*, "Biocompatible Alginate Film Crosslinked with Ca^{2+} and Zn^{2+} Possesses Antibacterial, Antiviral, and Anticancer Activities," *ACS Omega*, vol. 8, no. 27, pp. 24396–24405, Jul. 2023, doi: 10.1021/acsomega.3c01935.

1.25. Appendix VII: Coated Sponge Fabrication Protocol

Gelatin Coated Sponge Fabrication Protocol

Materials:

- Polyurethane sponge
- 14 Fr Salem Sump Tube
- Surgical scissors
- Suture
- 25cm x 25cm gelatin sheet
- 1.5cm mold
- Label tape
- Oven
- Fridge

Procedure

1. Create sponge tube system
    a. Cut the sponge to a 3cm diameter and cut edges down the length of the sponge to create a rounded shape
    b. Use surgical scissors to cut a hole though the center of the sponge
    c. Push the tube through the hole in the sponge until all holes are covered
    d. Use a suture to attach the tube to the sponge

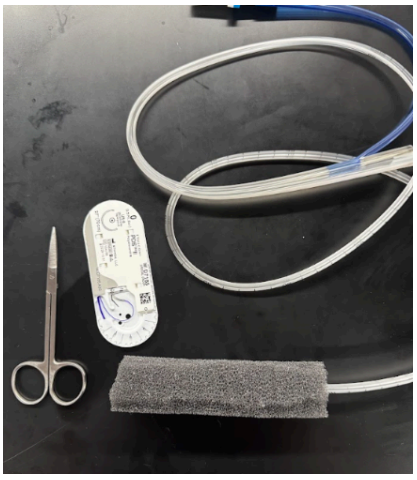

Figure 1. Sponge-tube system assembled and prepared to be sutured

2. Gelatin coating
    a. Cut a 7cm x 10cm rectangle of gelatin from the sheet

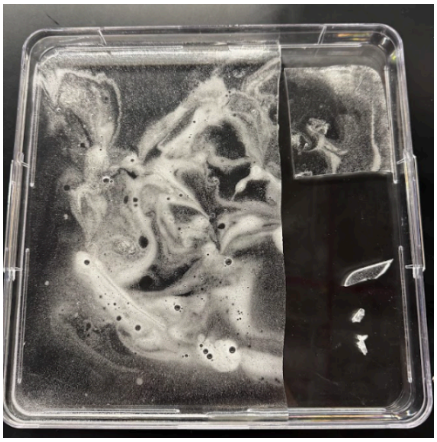

Figure 2. 7cmx10cm rectangle cut from the 25cmx25cm gelatin sheet.

b. Place the gelatin rectangle in the bottom mold
c. Squeeze the sponge and push it between the gelatin
d. Use the top mold piece to compress the gelatin and sponge
e. Tape the top and bottom mold pieces together so the sponge remains compressed

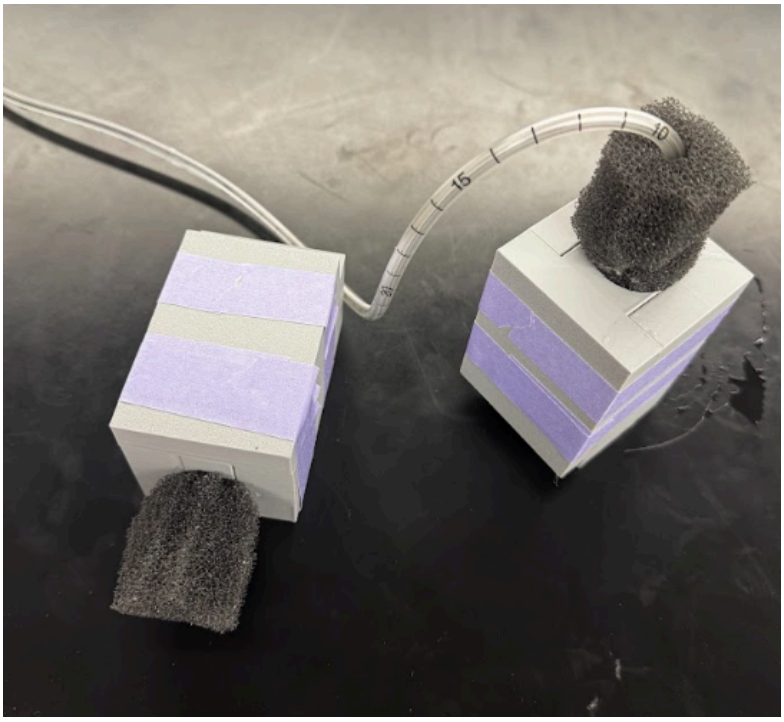

Figure 3. Sponge compression molds in use

f. Place the mold in the oven at 50℃ for 10 minutes until gelatin is softened
g. Place the mold standing upright in the fridge to solidify (~30 minutes)

3. Type of Coating
    a. Hydrogel: remove the sponge from the mold and store in fridge until use
    b. Film: remove the sponge from the mold and leave out to dry

1.26. Appendix VIII: Degradation Testing Protocol

Coating Material Degradation Testing Protocol

Objective: Measure the degradation of coating to assess performance in simulated gastrointestinal tract conditions.

Materials:

- 6 gelatin hydrogel samples
- 6 gelatin film samples
- 6 sodium alginate samples
- 18 50mL beakers (one per sample)
- Phosphate Buffered Saline (PBS) working solution (1X, pH 7.4 ± 0.2)
    - 10X PBS stock solution (pH 7.4, 0.2 µm filtered) diluted 1:9 with DI water

Phosphate buffered saline | Protocols Online

- Incubator at 37°C +/- 1°C
- pH strips
- Temperature probe
- Fisher Science Education Portable Balance, Model: SLF303
- 25mL serological pipette: Falcon 357525

Procedure:

1. Preheat incubator and let it reach 37°C
2. Prepare PBS solution: dilute 50 mL of 10X PBS stock into 450 mL distilled water to yield 500 mL of 1X working solution.
3. Use serological pipette to put 20mL of PBS solution into each 50mL beaker
4. Set all 500mL containers with diluted PBS solution and put in the preheated incubator and leave to warm up overnight
5. Weigh each sample prior to being in solution and mark weight
6. Record the initial pH and temperature of PBS solution
7. Immerse 1 samples per 50mL container with PBS solution and record weights at 5, 10, 15, 20, 25, 30, 60, 90 minutes
8. At each time interval, remove samples from PBS, place on a paper towel and blot gently with a second paper towel using consistent pressure (3 blots). Immediately transfer to a tared weighing boat and record mass. Return sample to PBS within 2 minutes of removal.
9. Record the pH and temperature of PBS solution at each interval
10. If at any point the same is completely disintegrated, mark weight as 0g and mark the time it was measured.

1.27. Appendix IX: Degradation Analysis MATLAB Code

1.27.1. Uncovered Gelatin Degradation Initial Mass Variance Plot

```
%% Degradation Analysis - Uncovered Gelatin Film
clc; clear; close all;
%% DATA ENTRY
time = [0, 5, 10, 15, 20, 25, 30, 35, 40, 45, 60, 90, 100];
all_initial_mass = [0.36, 0.33, 0.33, 0.35, 0.32, 0.31];
raw_mass = [
  0.36,  0.33,  0.33,  0.35,  0.32,  0.31;
  0.60,  0.62,  0.617, 0.60,  0.60,  0.59;
  0.72,  0.67,  0.687, 0.70,  0.68,  0.72;
  0.78,  0.758, 0.84,  0.74,  0.80,  0.80;
  0.94,  0.867, 0.91,  0.89,  0.88,  0.894;
  1.034, 0.92,  1.03,  0.977, 0.944, 0.95;
  1.102, 1.014, 1.117, 1.08,  1.031, 1.057;
  1.22,  1.06,  1.16,  1.167, 1.08,  1.10;
  1.27,  1.18,  1.23,  1.166, 1.15,  1.104;
  1.30,  1.22,  1.32,  1.18,  1.168, 1.11;
  1.43,  1.32,  1.42,  1.46,  1.41,  1.29;
  0.30,  0.47,  0.18,  0.10,  0.30,  0.13;
  0,     0,     0,     0,     0,     0;
];
%% STATISTICS
mean_mass = mean(raw_mass, 2);
sd_mass   = std(raw_mass, 0, 2);
pct_individual = (raw_mass ./ raw_mass(1,:)) * 100;
pct_remaining  = mean(pct_individual, 2);
pct_sd         = std(pct_individual, 0, 2);
%% PEAK SWELLING
[peak_pct, peak_idx] = max(pct_remaining);
peak_time = time(peak_idx);
fprintf('Uncovered Gelatin -Results \n');
fprintf('Initial mean mass:          %.3f g\n', mean_mass(1));
fprintf('SD of initial mass:         %.3f g (%.1f%% of mean)\n', ...
  sd_mass(1), (sd_mass(1)/mean_mass(1))*100);
fprintf('Peak swelling:              %.1f%% at t = %d min\n', peak_pct, peak_time);
fprintf('Complete dissolution:       between 90 and 100 min\n\n');
%% LINEAR FIT (dissolution phase: 60-100 min)
diss_mask  = time >= peak_time;
time_diss  = time(diss_mask);
```

```
pct_diss   = pct_remaining(diss_mask);
p_lin = polyfit(time_diss, pct_diss, 1);
slope_val = p_lin(1);
intercept = p_lin(2);
pct_fit_pts = polyval(p_lin, time_diss);
ss_res = sum((pct_diss - pct_fit_pts).^2);
ss_tot = sum((pct_diss - mean(pct_diss)).^2);
r_sq   = 1 - ss_res / ss_tot;
t_zero = -intercept / slope_val;
fprintf(' Linear Fit (60-100 min)\n');
fprintf('Slope:                %.3f %%/min\n', slope_val);
fprintf('R-squared:              %.3f\n', r_sq);
fprintf('Extrapolated t = 0%%:       %.1f min\n\n', t_zero);
t_fit_range = linspace(peak_time, t_zero, 300);
pct_fit     = polyval(p_lin, t_fit_range);
pct_fit(pct_fit < 0) = 0;
%% FIGURE 1 - Full degradation curve
figure('Name', 'Uncovered Gelatin Degradation', 'Position', [100 100 850 540]);
hold on;
y_max = max(pct_remaining + pct_sd) + 20;
patch([0, peak_time, peak_time, 0], [0, 0, y_max, y_max], ...
  [0.8 0.9 1.0], 'FaceAlpha', 0.2, 'EdgeColor', 'none', ...
  'DisplayName', 'Swelling phase');
patch([peak_time, 103, 103, peak_time], [0, 0, y_max, y_max], ...
  [1.0 0.85 0.85], 'FaceAlpha', 0.2, 'EdgeColor', 'none', ...
  'DisplayName', 'Dissolution phase');
x_band = [time, fliplr(time)];
y_band = [pct_remaining' + pct_sd', fliplr(pct_remaining' - pct_sd')];
fill(x_band, y_band, [0.85 0.85 0.85], 'FaceAlpha', 0.4, ...
  'EdgeColor', 'none', 'DisplayName', '\pm 1 SD band');
errorbar(time, pct_remaining, pct_sd, 'ko-', ...
  'LineWidth', 2, 'MarkerSize', 7, 'MarkerFaceColor', 'k', ...
  'CapSize', 6, 'DisplayName', 'Mean \pm SD (n=6)');
plot(t_fit_range, pct_fit, 'r--', 'LineWidth', 2, ...
  'DisplayName', 'Linear fit (dissolution phase)');
plot(peak_time, peak_pct, 'b^', 'MarkerSize', 10, 'MarkerFaceColor', 'b', ...
  'DisplayName', sprintf('Peak swelling (%d min)', peak_time));
yline(100, 'k:', 'LineWidth', 1, 'DisplayName', 'Initial mass (100%)');
text(t_zero - 1, 18, ['Slope = ' sprintf('%.1f', slope_val) ' %/min'], ...
  'FontSize', 9, 'FontName', 'Arial', 'Color', 'r', ...
```

```
  'HorizontalAlignment', 'right');
hold off;
xlabel('Time (min)', 'FontSize', 12);
ylabel('Mass remaining relative to t=0 (%)', 'FontSize', 12);
title('Uncovered Gelatin Film — Swelling and Dissolution in PBS (pH 7.4, 37°C)', ...
  'FontSize', 13);
legend('Location', 'northeast', 'FontSize', 9);
xlim([-2 103]);
ylim([0 y_max]);
grid on; box on;
set(gca, 'FontSize', 11);
%% FIGURE 2 - Initial mass variance
figure('Name', 'Initial Mass Variance', 'Position', [950 100 520 420]);
bar_h = bar(1:6, all_initial_mass, 'FaceColor', [0.6 0.6 0.6], 'EdgeColor', 'k');
xlabel('Sample number', 'FontSize', 12);
ylabel('Initial mass at t=0 (g)', 'FontSize', 12);
title('Uncovered Gelatin — Initial Sample Mass at t=0 (n=6)', 'FontSize', 12);
ylim([0 max(all_initial_mass) + 0.1]);
xticks(1:6);
grid on; box on;
set(gca, 'FontSize', 11);
```

1.27.2. Sodium Alginate Degradation and Initial Mass Variance Plot

```
%% Degradation Analysis - Sodium Alginate Crosslinked with CaCl2
clc; clear; close all;
%% DATA
time = [0, 5, 10, 15, 20, 25, 30, 35, 40, 45, 60, 90];
% All 6 samples
all_initial_mass = [1.275, 1.67, 1.70, 1.316, 1.13, 1.25];
% Degradation analysis
raw_mass = [
  1.67,  1.70,  1.316, 1.13,  1.25;   % 0 min
  1.80,  1.80,  1.42,  1.23,  1.40;   % 5 min
  2.04,  1.53,  1.48,  1.17,  1.58;   % 10 min
  2.05,  2.12,  1.55,  1.01,  1.24;   % 15 min
  2.10,  1.99,  1.72,  0.97,  1.10;   % 20 min
  2.13,  1.97,  1.61,  0.91,  0.99;   % 25 min
  1.88,  1.80,  1.54,  0.78,  0.87;   % 30 min
  1.66,  1.73,  1.45,  0.67,  0.82;   % 35 min
  1.43,  1.58,  1.39,  0.59,  0.79;   % 40 min
```

```
    1.19,  1.40,  1.32,  0.51,  0.72;   % 45 min
    1.05,  1.30,  1.25,  0.45,  0.71;   % 60 min
    0.50,  0.45,  0.78,  0.32,  0.25;   % 90 min
];
%% STATISTICS
mean_mass = mean(raw_mass, 2);
sd_mass = std(raw_mass, 0, 2);
pct_individual = (raw_mass ./ raw_mass(1,:)) * 100;
pct_remaining = mean(pct_individual, 2);
pct_sd = std(pct_individual, 0, 2);
fprintf('Sodium Alginate - Results \n');
fprintf('Mean initial mass:          %.3f g\n', mean_mass(1));
fprintf('SD of initial mass:         %.3f g (%.1f%% of mean)\n', ...
    sd_mass(1), (sd_mass(1)/mean_mass(1))*100);
fprintf('%% mass remaining at 30 min: %.1f%%\n', pct_remaining(time==30));
fprintf('%% mass remaining at 45 min: %.1f%%\n', pct_remaining(time==45));
fprintf('%% mass remaining at 60 min: %.1f%%\n', pct_remaining(time==60));
fprintf('%% mass remaining at 90 min: %.1f%%\n\n', pct_remaining(time==90));
%% LINEAR FIT (dissolution phase 30-90 min)
decay_mask = time >= 30;
time_decay = time(decay_mask);
pct_decay = pct_remaining(decay_mask);
p = polyfit(time_decay, pct_decay, 1);
m = p(1);
b = p(2);
t_zero = -b / m;
fprintf(' Linear Fit (30-90 min) \n');
fprintf('Slope:                      %.3f %%/min\n', m);
fprintf('Extrapolated t = 0%%:       %.1f min\n\n', t_zero);
t_fit_range = linspace(30, t_zero, 300);
pct_fit = polyval(p, t_fit_range);
%% PEAK SWELLING
[peak_pct, peak_idx] = max(pct_remaining);
peak_time = time(peak_idx);
fprintf('Peak swelling:              %.1f%% at t = %d min\n\n', peak_pct, peak_time);
%% FIGURE 1 - Full degradation curve
figure('Name', 'Sodium Alginate Degradation', 'Position', [100 100 850 540]);
hold on;
y_max = max(pct_remaining + pct_sd) + 30;
patch([0, peak_time, peak_time, 0], [0, 0, y_max, y_max], ...
```

```
  [0.8 0.9 1.0], 'FaceAlpha', 0.2, 'EdgeColor', 'none', ...
  'DisplayName', 'Swelling phase');
patch([peak_time, 100, 100, peak_time], [0, 0, y_max, y_max], ...
  [1.0 0.85 0.85], 'FaceAlpha', 0.2, 'EdgeColor', 'none', ...
  'DisplayName', 'Dissolution phase');
x_band = [time, fliplr(time)];
y_band = [pct_remaining' + pct_sd', fliplr(pct_remaining' - pct_sd')];
fill(x_band, y_band, [0.85 0.85 0.85], 'FaceAlpha', 0.4, ...
  'EdgeColor', 'none', 'DisplayName', '\pm 1 SD band');
% Mean with error bars
errorbar(time, pct_remaining, pct_sd, 'ko-', ...
  'LineWidth', 2, 'MarkerSize', 7, 'MarkerFaceColor', 'k', ...
  'CapSize', 6, 'DisplayName', 'Mean \pm SD (n=5)');
% Linear fit
plot(t_fit_range, pct_fit, 'r--', 'LineWidth', 2, ...
  'DisplayName', ['Linear fit (est. dissolution: ' sprintf('%.0f', t_zero) ' min)']);
% Peak swelling marker
plot(peak_time, peak_pct, 'b^', 'MarkerSize', 10, 'MarkerFaceColor', 'b', ...
  'DisplayName', sprintf('Peak swelling (%d min)', peak_time));
% Initial mass reference
yline(100, 'k:', 'LineWidth', 1, 'DisplayName', 'Initial mass (100%)');
% Slope label directly on the red line
text(88, polyval(p, 88) + 6, ['Slope = ' sprintf('%.3f', m) ' %/min'], ...
  'FontSize', 9, 'FontName', 'Arial', 'Color', 'r', ...
  'HorizontalAlignment', 'left');
hold off;
xlabel('Time (min)', 'FontSize', 12);
ylabel('Mass remaining relative to t=0 (%)', 'FontSize', 12);
title('Sodium Alginate (CaCl_2 crosslinked) — Degradation in PBS (pH 7.4, 37°C)', ...
  'FontSize', 13);
legend('Location', 'southwest', 'FontSize', 9);
xlim([-2 100]);
ylim([0 y_max]);
grid on; box on;
set(gca, 'FontSize', 11);
%% FIGURE 2 - Initial mass variance
figure('Name', 'Initial Mass Variance', 'Position', [950 100 520 420]);
b = bar(1:6, all_initial_mass, 'FaceColor', [0.6 0.6 0.6], 'EdgeColor', 'k');
xlabel('Sample number', 'FontSize', 12);
ylabel('Initial mass at t=0 (g)', 'FontSize', 12);
```

```
title('Sodium Alginate — Initial Sample Mass at t=0 (n=6)', 'FontSize', 12);

ylim([0 max(all_initial_mass) + 0.3]);
grid on; box on;
set(gca, 'FontSize', 11);
xticks(1:6);
```

1.28. Appendix X: Sponge Expansion Testing Protocol

Coating Material Degradation Testing

Objective: Measure the degradation of coating to assess performance in simulated gastrointestinal tract conditions.

Materials:

- 6 gelatin hydrogel samples
- 6 gelatin film samples
- 6 sodium alginate samples
- 18 50mL beakers (one per sample)
- Phosphate Buffered Saline (PBS) working solution (1X, pH 7.4 ± 0.2)
    - 10X PBS stock solution (pH 7.4, 0.2 µm filtered) diluted 1:9 with DI water

Phosphate buffered saline | Protocols Online

- Incubator at 37°C +/- 1°C
- pH strips
- Temperature probe
- Fisher Science Education Portable Balance, Model: SLF303
- 25mL serological pipette: Falcon 357525

Procedure:

1. Preheat incubator and let it reach 37°C
2. Prepare PBS solution: dilute 50 mL of 10X PBS stock into 450 mL distilled water to yield 500 mL of 1X working solution.
3. Use serological pipette to put 20mL of PBS solution into each 50mL beaker
4. Set all 500mL containers with diluted PBS solution and put in the preheated incubator and leave to warm up overnight
5. Weigh each sample prior to being in solution and mark weight
6. Record the initial pH and temperature of PBS solution
7. Immerse 1 samples per 50mL container with PBS solution and record weights at 5, 10, 15, 20, 25, 30, 60, 90 minutes
8. At each time interval, remove samples from PBS, place on a paper towel and blot gently with a second paper towel using consistent pressure (3 blots). Immediately transfer to a tared weighing boat and record mass. Return sample to PBS within 2 minutes of removal.
9. Record the pH and temperature of PBS solution at each interval
10. If at any point the same is completely disintegrated, mark weight as 0g and mark the time it was measured.

1.29. Appendix XI: Sponge Expansion Analysis MATLAB Code

```
%% Sponge Diameter Analysis
clc; clear; close all;
%% BATCH 1 DATA
t_s1 = (0:20)';
d_s1 = [1.35,1.68,2.13,2.33,2.94,2.93,3.18,3.21,3.24,3.31,...
    3.32,3.37,3.44,3.55,3.64,3.71,3.75,3.79,3.82,3.82,3.82]';
t_m1 = (0:20)';
d_m1 = [1.21,1.41,1.63,1.92,2.03,2.11,2.17,2.22,2.23,2.26,...
    2.31,2.47,2.54,2.51,2.61,2.72,2.82,3.07,3.09,3.13,3.13]';
t_e1 = (0:20)';
d_e1 = [1.62,2.09,2.41,2.72,3.03,3.34,3.63,3.65,3.71,3.82,...
    3.91,4.00,4.00,4.09,4.18,4.18,4.21,4.21,4.24,4.21,4.21]';
%% BATCH 2 DATA
t_s2 = (0:20)';
d_s2 = [1.33,1.91,2.17,2.38,2.67,2.99,2.92,2.96,2.99,3.01,...
    3.07,3.09,3.17,3.23,3.27,3.31,3.34,3.36,3.43,3.68,3.68]';
t_m2  = (0:20)';
d_m2  = NaN(21,1);
d_m2(1)  = 1.35;
d_m2(2)  = 1.61;
d_m2(3)  = 1.84;
d_m2(5)  = 1.92;
d_m2(6)  = mean([2.03, 2.36]);
d_m2(11) = 2.46;
d_m2(12) = 2.57;
d_m2(14) = 2.77;
d_m2(15) = 2.88;
d_m2(16) = 2.92;
d_m2(17) = 3.04;
d_m2(19) = 3.08;
d_m2(21) = 3.17;
t_e2 = (0:20)';
d_e2 = [1.27,1.85,1.93,2.05,2.11,2.39,2.74,2.94,3.29,3.32,...
    3.52,3.58,3.61,3.69,3.69,3.72,3.81,3.78,3.78,3.84,3.84]';
%% TIME GRID
t_max    = 20;
t_common = (0:t_max)';
D = [d_s1, d_m1, d_e1, d_s2, d_m2, d_e2];
%% PERCENT EXPANDED
```

```
% 0% = initial compressed size at t=0
% 100% = fully expanded size at t=20
D_pct = ((D - D(1,:)) ./ (D(end,:) - D(1,:))) * 100;
%% MEAN & SD of percent expanded
mean_pct = mean(D_pct, 2, 'omitnan');
sd_pct   = std(D_pct,  0, 2, 'omitnan');
n_valid  = sum(~isnan(D_pct), 2);
%% ASYMPTOTIC FIT
valid_idx = ~isnan(mean_pct);
t_fit     = t_common(valid_idx);
d_fit     = mean_pct(valid_idx);
model  = @(p, t) p(1)*(1 - exp(-p(2)*t)) + p(3);
objfun = @(p) sum((d_fit - model(p, t_fit)).^2);
p0      = [100, 0.2, 0];
options = optimset('MaxFunEvals',10000, 'MaxIter',10000, ...
                   'TolFun',1e-10, 'TolX',1e-10);
p_opt   = fminsearch(objfun, p0, options);
d_pred  = model(p_opt, t_fit);
ss_res  = sum((d_fit - d_pred).^2);
ss_tot  = sum((d_fit - mean(d_fit)).^2);
rsquare = 1 - ss_res/ss_tot;
t_smooth   = linspace(0, t_max, 300)';
pct_smooth = model(p_opt, t_smooth);
plateau_pct = p_opt(1) + p_opt(3);
fprintf('=== Asymptotic Fit (Percent Expanded) ===\n');
fprintf('Plateau expansion:  %.1f%%\n', plateau_pct);
fprintf('Rate constant k:    %.4f /min\n', p_opt(2));
fprintf('R-squared:          %.4f\n\n', rsquare);
%% SHARED AXIS LIMITS
x_lim = [-0.5, t_max + 0.5];
y_lim = [-10, 120];
%% SD BAND
valid_band = ~any(isnan([mean_pct+sd_pct, mean_pct-sd_pct]), 2);
x_band = [t_common(valid_band); flipud(t_common(valid_band))];
y_band = [mean_pct(valid_band)+sd_pct(valid_band); ...
          flipud(mean_pct(valid_band)-sd_pct(valid_band))];
%% FIGURE
figure('Name','Sponge Expansion','Position',[100 100 1100 700]);
hold on;
fill(x_band, y_band, [0.75 0.75 0.75], 'FaceAlpha',0.4, ...
```

```
  'EdgeColor','none', 'DisplayName','\pm 1 SD');
errorbar(t_common, mean_pct, sd_pct, 'ko-', 'LineWidth',2.5, 'MarkerSize',8, ...
  'MarkerFaceColor','k', 'CapSize',6, ...
  'DisplayName','Grand mean \pm SD (n=6)');
plot(t_smooth, pct_smooth, 'm--', 'LineWidth',2.5, ...
  'DisplayName', sprintf('Fit: d = A(1-e^{-kt}) + d_0  (R²=%.3f)', rsquare));
hold off;
xlabel('Time (min)',    'FontSize',24, 'FontWeight','bold');
ylabel('Expansion (%)', 'FontSize',24, 'FontWeight','bold');
title('Sponge Expansion Over Time', 'FontSize',35, 'FontWeight','bold');
legend('Location','southeast', 'FontSize',18);
xlim(x_lim); ylim(y_lim);
grid on; box on;
set(gca,'FontSize',20,'FontWeight','bold');
%% SUMMARY TABLE
fprintf('=== Summary Table ===\n');
fprintf('%-10s %-15s %-12s %-10s\n','Time(min)','Mean Exp(%)','SD(%)','n');
fprintf('%s\n', repmat('-',1,50));
for i = 1:length(t_common)
  fprintf('%-10d %-15.1f %-12.1f %-10d\n', ...
    t_common(i), mean_pct(i), sd_pct(i), n_valid(i));
end
```